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Chicago, Illinois

SUMMARY
OF
RESEARCH REPORT

SHELTER HABITABILITY IN EXISTING BUILDINGS
UNDER FIRE EXPOSURE

by

Thomas E. Waterman

June, 1966

Prepared for
Office of Civil Defense
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Radiological Defense Laboratory, San Francisco, California
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OBJECTIVE AND SCOPE

The objectives of this contract are to yield some preliminary information regarding the habitability of fallout shelters in existing buildings (similar to those marked in the National Fallout Shelter Survey) under fire exposure, and to provide background information regarding the feasibility of local fire and engineering people to obtain meaningful data from building burns. These are to be achieved by designing and conducting fire tests in 3 buildings in Waukesha, Wisconsin in cooperation with the Waukesha Fire Department and the State of Wisconsin.

PROBLEM DISCUSSION

Fire behavior in a shelter building must be examined in a frame of reference which is different from that used for war-time damage assessment or peace-time fire safety. For damage assessment, one is concerned mainly with the time for spread through structures as it affects the ability of the fire to spread to adjacent structures. For peacetime fire safety purposes, rate of spread and smoke production assume great importance in terms of establishing a safe exiting time for building occupants. In fact, building component fire ratings imply that evacuation of the building is possible, that organized fire fighting is readily available, and that adequate water supplies exist.

For shelter considerations, the evacuation of the building is not desirable and fire fighting is limited to that of the occupants under severe restrictions imposed by the existence of radioactive fallout and a shortage of water. Furthermore, for shelter safety, full building involvement cannot be tolerated and, since population internment for the fire duration is required, the production and movement of hot and/or toxic gases assume major importance.

It should be recognized that the assessment of the environment within shelter spaces can be approached in two ways. The first is to study experimentally a large number of shelters having various barriers in many locations within the structures. This approach requires the collection of data on many fires but instrumentation could probably be fairly simple. The second approach consists of the following two steps:

1. Establishing the conditions (temperature, heat flux, gas concentration) surrounding any shelter as a function of building geometry and the shelter location relative to the fire(s).
2. Evaluating the ability of those shelter components forming barriers to resist the penetration of heat and toxic gases (in terms of "leakage rates" related to the degree of degradation of the barrier).

The first step requires a certain amount of data obtainable only in full-scale building fires but the second step can be treated in the laboratory.⁽²⁾ This latter approach has the advantage that it permits systematic evaluation of shelter components; the results obtained can then be used to interpret the performance of any combination of these components forming a real shelter. A further advantage of this approach is that in experimental burns, data can be collected throughout the structure since any area can be assumed to be adjacent to the shelter.

In the experiments, therefore, no emphasis was placed on designating specific areas of the building as shelters, and in fact, only one shelter area was specified.

DESCRIPTION OF EXPERIMENT

An experimental program was conducted for determining the production of hot and/or toxic gases and the forces and restrictions influencing their movement throughout the structures. The experiments were performed in three

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buildings located in the city of Waukesha, Wisconsin. The structures presented a minimum exposure problem and were suitable for a variety of investigations. Full cooperation of the Waukesha Fire Department, the State of Wisconsin and the Civil Defense Agency of the State of Wisconsin was assured. In fact, the opportunity to contribute to the program was enthusiastically received by other fire departments in the area through Mr. W. E. Clark, Supervisor of Fire Service Training of the State of Wisconsin, who brought the availability of the structures to the attention of OCD and IITRI.

Due to limitations on funds and time (the land was scheduled to be cleared by early summer, 1965) only three of the available seventeen structures, were used for the experimentations. Buildings 1 and 2, two structures each 63 x 37 ft. and three-stories high, were of masonry and wood joist construction; and selected portions of both were modified to simulate fire resistive construction. In both structures, major instrumentation was concentrated at or above the level of the initially ignited room. Building 3, also of masonry and wood joist construction, 90 x 160 ft. and two-stories high, had a fire resistive portion, which isolated a part of the basement from the rest of the structure.

Building No. 1

Two experiments were conducted in Building 1. In each the fire was started in a first floor room. This room and a portion of the adjacent one were lined with gypsum board and sheet metal to extend the period during which the fires resembled those which would occur in a fire resistive structure. Doors within the structure were arranged so that smoke and hot gases were channeled across the first floor and upward through a stairwell to the third floor level. External openings were protected with sheet metal curtains extending downward to within several inches of the window

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sills. In the first experiment all doors and windows (except in the room of origin) were tightly closed. In the second experiment, a small opening was made in the door at the third floor to permit some bulk gas flow up the stairwell. These experiments can be considered similar to those conducted in "Operation School Burning"⁽³⁾ except that here a deliberate attempt was made to minimize the volume available for dilution of the fire gases and to maximize the pressure buildup in the stairwell.

Fuel loading in the room of origin consisted of a large wood crib (2 x 4 inch lumber) for each experiment, which was weighed continuously during the burn. The remainder of the structure was loaded with furniture to a typical residential condition.

Temperatures, pressures and CO and O₂ concentrations were monitored at various points along the path of the fire gases. Gas flow was measured at the third floor door opening in Experiment No. 2. Weight losses of fuels in the room of origin were recorded as well as radiant heat fluxes from the openings.

Building No. 2

In all its essential features, Building No. 2 was the same as Building No. 1. One experiment was conducted in this building. The room of fire origin was on the second floor, and the path for smoke and gas spread and the volume available along the path were similar to those in Building 1. Again, the room of origin and a portion of the adjacent one were lined with gypsum board and sheet metal. Also, windows and doors were tightly closed (except in the room of origin) and protected where necessary.

Fuel loading of Building No. 2 was similar to that used in Building No. 1, and the same kind of data was obtained.

Building No. 3

This structure, also of masonry and wood joist construction, was two-stories high with a large attic. It was about 90 x 160 feet and had apparently been two separate constructions. The exterior walls and a number of interior partitions were of brick.

Because of the large room area and volume afforded by a dining hall (60 x 90 x 18 feet high), it was used to examine the minimum water requirement for extinguishment of fire in this size room. Upon completion of the extinguishment experiments, the fire was allowed to rekindle and spread throughout the structure.

The basement area under the newer portion had a poured concrete ceiling and could be considered fire resistive. Conditions in and around this fire resistive basement area, designated during experiments as a shelter area, were monitored during the structural burnout. The suitability of the basement for use as a shelter was analyzed by M. P. Gronbeck, a qualified shelter analyst.

CONCLUSIONS

The conclusions derived from the experiments are listed below.

1) Oxygen depletion in an active fire zone will be reproduced throughout interconnecting spaces on the same or higher stories of a relatively "tight" structure or structural portion (unless very large volumes are being considered). In experiments with Buildings 1 and 2, O_2 levels as low as 5% O_2 were measured.

2) CO concentration of about 75% of those in the active fire zone would have existed at the exterior of shelters removed from the fire but on the same or higher level. A maximum of 3.3% CO was recorded in these specific experiments.

3) Wind pressures can drive fire gases into shelter spaces even if fire generated pressures are not significant. Smouldering fires may produce significant infiltration of toxic gases by this means.

4) Although much more data is needed on real fire environments and movement of fire gases through complex structures, the above conclusions lead to a further statement that fires within a "tight" envelope bounded in part by a shelter cannot be tolerated and must be extinguished unless the barrier between the fire and the shelter is perfectly gas tight.

5) In a fire resistive construction, downward movement of CO will probably not occur.

6) Fire gases infiltrating a shelter having otherwise cool floor, walls, and ceiling do not significantly heat the shelter air space and would represent a hazard only because of toxicity or the ignition of combustibles within the shelter. In Building No. 3, the CO concentration stayed below 0.05% in the shelter, however, not much higher concentration occurred outside the shelter in this particular fire.

7) The external heating of walls, floor or ceiling in a shelter is a significant hazard and the effects are likely to be long lasting because of the large heat capacity of the shelter envelope. In this respect, the presence of burning combustibles mixed with non-combustibles in direct contact with the shelter produces long-term heating and is particularly dangerous. Ceiling temperature in the designated shelter area of Building No. 3 reached 130°F which lasted well over 24 hours for a rather moderate debris piling.

8) Due to the cooling effect of walls and ceilings, the temperatures of gases moving horizontally within a structure fall rapidly and should not significantly degrade

barriers which are remote from the active fire zone. This is not necessarily true for vertical gas movements such as would occur when the fire and barrier being considered are separated only by a vertical shaft.

9) Provision for complete sealing of shelter vents to the outside may be necessary to prevent lowering of shelter pressure by suction through the vent. When outside conditions permit, the vent could be used to pump air into the shelter thus producing positive flow out through any voids in the shelter envelope.

10) Variations in construction, otherwise considered minor, may have a significant effect on firebrand generation. This subject needs further investigation.

11) Local fire and engineering services can collect meaningful data from building burns. They lack only guidance toward a more detailed understanding of the non-extinguishment aspects of fires and the specific interests of shelter safety.

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ABSTRACT

Experiments were performed in full scale buildings to obtain information regarding the habitability of fallout shelters in existing buildings under fire exposure. One two-story and two three-story buildings of masonry and wood joist construction were used. The fire load of the room of fire origin consisted of a large crib (2 x 4 inch lumber) with the remainder of the structures loaded with furniture typical of residential construction.

In two of the buildings, the spread of heat, smoke and toxic gases was monitored throughout the buildings for fires contained within one room. In the other building, conditions (temperature, pressure, and CO concentration) were monitored in and around a fire-resistive basement shelter during complete burnout of the structure. Radiant heat fluxes emitted at window openings were measured in all of the experiments.

Results indicate that oxygen depletion in an active fire zone will be reproduced throughout interconnecting spaces. Carbon monoxide concentrations of 75 percent of those in the active fire zone were found at places removed from the fire but on the same or higher levels.

For these buildings, wind-induced pressure differences were greater than fire-induced pressure differences and thus would have had greater effect on the infiltration of fire

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gases through shelter barriers. The long lasting effects of debris fires in contact with the shelter were found to produce dangerous heating of the shelter.

In addition to other pertinent observations, the experiments have also demonstrated that local fire and engineering services, if given proper guidance, can collect meaningful data from building burns.

PREFACE

This is the final report on Contract No. N228(62479)68355, T. O. 64-200(36), OCD No. 1133C (IITRI Project No. M6121), "Shelter Habitability in Existing Buildings under Fire Exposure". The program is sponsored by the Department of the Army, Office of the Secretary of the Army, Office of Civil Defense, through the U. S. Naval Radiological Defense Laboratory. The contract was initiated in April, 1965.

IIT Research Institute personnel who contributed to the program include D. Carter, J. Marolda, W. J. Murphy, F. Salzberg, F. J. Vodvarka and T. E. Waterman.

Consultants were Professor M. P. Gronbeck of the Wisconsin State College and Institute of Technology (a qualified shelter analyst), Chief C. Rule of the Greenfield, Wisconsin, Fire Department and Chief J. Pavlik of the West Milwaukee Fire Department.

Special thanks go to Mr. W. E. Clark, Supervisor of Fire Service Training, Wisconsin State Board of Vocational and Adult Education who brought the availability of the structures to our attention. He also coordinated the fire protection during all tests, and supervised the extinguishment experiments described in Appendix B. We also wish to express our appreciation to the City of Waukesha, Wisconsin, for providing the buildings. Close cooperation was received from all city departments; in particular, Chief E. Downie and the Waukesha firemen provided

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invaluable service both during the burns and throughout the period of building preparation and instrumentation.

Respectfully submitted,

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TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
I	INTRODUCTION	1
II	SHELTER FIRE PROBLEMS	3
	A. Differences from Peacetime Situation. . .	3
	B. Characteristics of Existing Shelters. . .	4
	C. Assessment of Shelter Habitability. . . .	5
III	EXPERIMENTS	7
	A. Building No. 1.	7
	B. Building No. 2.	11
	C. Building No. 3.	15
IV	RESULTS.	32
	A. The Fires.	32
	1. Crib Fires--Buildings No. 1 and 2 . . .	32
	2. Fire History of Building No. 3. . . .	40
	B. Temperatures.	45
	1. Buildings No. 1 and 2	45
	2. Building No. 3.	50
	C. Gases	50
	1. Buildings No. 1 and 2	52
	2. Building No. 3	58
	D. Pressure.	60
	E. Firebrands	65

TABLE OF CONTENTS (Cont'd)

<u>Section</u>	<u>Page</u>
F. Miscellaneous	69
1. Ignition of Laundry Building . .	69
2. Condition after Fire	70
V CONCLUSIONS	73
VI USE OF LOCAL FIRE ENGINEERING SERVICES FOR BUILDING BURNS.	76
VII RECOMMENDATIONS	85
REFERENCES.	92
APPENDICES	
A. Instrumentation	A-1
B. Extinguishment Studies.	B-1

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Building No. 1 (Waukesha, Wisconsin)	9
2	Schematic Cross Section of Building No. 1 (Waukesha, Wisconsin)	10
3A	First Floor, Building No. 1 (Waukesha, Wisconsin)	12
3B	Second Floor, Building No. 1 (Waukesha, Wisconsin)	13
3C	Third Floor, Building No. 1 (Waukesha Wisconsin)	14
4	Schematic Cross Section of Building No. 2 (Waukesha, Wisconsin)	16
5A	First Floor, Building No. 2 (Waukesha, Wisconsin)	17
5B	Second Floor, Building No. 2 (Waukesha Wisconsin)	18
5C	Third Floor, Building No. 2 (Waukesha Wisconsin)	19
6	Photographs of Building No. 3	21
7A	Basement Floor Plan, Building No. 3	22
7B	First Floor Plan, Building No. 3	23
7C	Second Floor Plan, Building No. 3	24
8	Photographs of Attic Spaces Building No. 3 (Waukesha, Wisconsin)	25
9	Detail of Basement Area, Building No. 3 . .	27
10	Windows in Basement Area Near Shelter Building No. 3 (Waukesha, Wisconsin)	29
11	Temperature Measurement in or near Shelter Area - Building No. 3 (Waukesha, Wisconsin)	30

LIST OF FIGURES (Cont.)

<u>Figure</u>		<u>Page</u>
12	Locations of Gas Sampling Points and Pressure Taps in Building No. 3 (Waukesha, Wisconsin)	31
13	Radiometers, Burn 3 (Waukesha, Wisconsin) . .	33
14	Crib Arrangement for Buildings 1 and 2 . . .	34
15	Burning Rate of Crib No. 1, Building No. 1 .	36
16	Burning Rate of Crib No. 2, Building No. 1 .	37
17	Air Flow from Stairwell Vent Experiment 2, Building 1	38
18	Burning Rate of Crib, Building No. 2	41
19	Plan View, Building No. 3.	42
20	Temperatures, Building No. 1, Experiment No. 1.	46
21	Building 1, Experiment 1	47
22	Temperatures, Building No. 2	48
23	Temperatures, Building No. 3	51
24	Gas Samples from Experiment 1, Building 1. .	53
25	Gas Samples from Experiment 2, Building 1... .	55
26	Gas Samples from Building No. 2.	57
27	Gas Samples from Building No. 3.	59
28	Experiment 1, Building 1	61
29	Experiment 2, Building 2	61
30	Pressure Records, Building No. 2	62
31	Pressure Differences Recorded During Burn #3 (Waukesha, Wisconsin)	63

LIST OF FIGURES (Cont.)

Figure		Page
32	Examples of Firebrands from Building No. 1. . .	67
33	Firebrands from Building No. 1.	68
34	Radiant Flux, Building No. 3 (Waukesha Wisconsin	71
35	Building No. 3 After the Fire	72
36	Shelter in Building 3 After the Fire.	74

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Fire History, Building 3.	43
2	Mass Spectrometer Analyses of Gases, Experiment 1, Building 1.	54

I. INTRODUCTION

It is well recognized that knowledge of free-burning fires has not kept pace with the rapid development of other branches of science. Motivated by an awareness of the enormous fire-starting capabilities of high yield nuclear weapons, numerous projects have been initiated in the field of free-burning fires to provide the data necessary to design defenses for urban areas against fires from nuclear bursts. Such studies can be generally classed as pertaining to 1) the environment created by free-burning fires, 2) their spread within and between structures, and 3) their suppression.

Each topic enters into planning of fire defenses. For example, the life hazard to shelter occupants from adjacent fires will depend on the resistance of barriers to heat, and the flow and type of combustion products. The magnitude of the pressures, temperatures and gas concentrations existing on the fire side of these barriers is a result of a complex interplay between the fire and the structure. Most of the topics listed above have been considered in the past. However, in many cases, the information obtained was only preliminary in nature. Since experiments with free-burning fires are expensive, much of the data was obtained from model fires. Before such information is accepted, portions of it must be verified by full-scale studies. Furthermore, in some areas, such as the study of heat and gas flow throughout structures, more information on

real structures under fire conditions is needed to properly design the laboratory procedures for detailed study.

Every year, for one reason or another, numerous structures are intentionally destroyed and often these structures are in excellent condition for the performance of fire experiments. All that need be added is the properly planned full-scale experiment which will result in useful data commensurate with the expended funds. This planning includes 1) the selection of the experiment(s) considering the type and condition of the structure, and 2) the assistance to be rendered by the local fire services. The latter is of great importance since the fire services represent a group of interested participants whose services can be utilized to greatly increase the quantity of information obtained. In fact, it is reasonable to consider that certain experiments could be conducted by local fire and engineering people operating with the aid of a prepared "guide" or "design manual" for fire experiments.

An opportunity to gain insight into all the preceding aspects of full-scale fire experiments presented itself in the city of Waukesha, Wisconsin, during the fall of 1964. A complex of 17 structures, ranging from 60 x 80 ft. to 90 x 155 ft., two and three stories high, were destined for destruction. These were of masonry and wood joist construction, except for a portion of one structure which was fire resistive. The structures presented a minimum exposure problem and were suitable for a

variety of investigations. Full cooperation of the Waukesha Fire Department, the State of Wisconsin and the Civil Defense Agency of the State of Wisconsin was assured. In fact, the opportunity to contribute to the program was enthusiastically received by other fire departments in the area through Mr. W. E. Clark, Supervisor of Fire Service Training of the State of Wisconsin, who brought the availability of the structures to the attention of OCD and IITRI.

Due to limitations on funds and time (the land was scheduled to be cleared by early summer 1965) all seventeen structures could not be considered, and three structures were reserved for experimentation under OCD work unit 1133C. The main objectives were to obtain preliminary information regarding the habitability of fallout shelters in existing buildings under fire exposure and to provide background information concerning the feasibility of using local fire services and engineering people to obtain data from building burns.

II. SHELTER FIRE PROBLEMS

A. Differences from the Peacetime Situation

Fire behavior in a shelter building must be examined in a frame of reference which is different from that used for war-time damage assessment or peacetime fire safety. For damage assessment, one is concerned mainly with the time for spread through structures as it affects the ability of the fire to spread to adjacent structures. For peacetime fire safety

purposes, rate of spread and smoke production assume great importance in terms of establishing a safe exiting time for the building population. In fact, building component fire ratings imply that evacuation of the building is possible, that organized fire fighting is readily available, and that adequate water supplies exist. For shelter considerations, the evacuation of the building is not desirable and fire fighting is limited to that of the occupants under severe restrictions imposed by the existence of radioactive fallout and a shortage of water. Furthermore, for shelter safety, full building involvement cannot be tolerated and, since population internment for the fire duration is required, the production and movement of hot and/or toxic gases assume major importance.

B. Characteristics of Existing Shelters

Based on a survey of a selected number of representative shelter buildings, Varley and Maatman⁽¹⁾ summarized characteristics of the shelter buildings as follows:

1. Fire resistive construction will be prevalent, although some unprotected steel and masonry wood joist structures may be found. Principal floor openings will generally be enclosed, but enclosures may be lacking in some localities.
2. The normal occupancies of most shelter buildings will consist of those types generally found in commercial and public buildings.

3. Significant numbers of portable extinguishers are to be found in a majority of buildings. Standpipe and hose installations are less often available. Automatic sprinkler systems are found for the most part only in particular types of occupancies.
4. Generally, fewer shelter areas will be found above-ground than below ground. However, the majority of the shelter population will be in above ground shelters.

Based on these findings and the considerations given earlier, the emphasis of the experimental program was placed on evaluation of the production of hot and/or toxic gases and the forces and restrictions influencing their movement throughout the structures. Those portions of the fire behavior resembling fires in a fire-resistive structure were considered to be of prime interest, and building modifications were undertaken to prolong this period of the fire development. The fact that a large portion of the sheltered population could be in above-ground shelters (due to a higher permissible occupant density in these shelters) led to consideration of situations where the fire was on the same or a lower level than the shelter.

C. Assessment of Shelter Habitability

It should be recognized that the assessment of the environment within shelter spaces can be approached in two ways. The first is to study experimentally a large number of shelters having various barriers in many locations within

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the structures. This approach requires the collection of data on many fires but instrumentation could probably be fairly simple. The second approach consists of the following two steps:

1. Establishing the conditions (temperature, heat flux, gas concentration) surrounding any shelter as a function of building geometry and the shelter location relative to the fire(s).
2. Evaluating the ability of those shelter components forming barriers to resist the penetration of heat and toxic gases (in terms of "leakage rates" related to the degree of degradation of the barrier).

The first step requires a certain amount of data obtainable only in full-scale building fires but the second step can be treated in the laboratory.⁽²⁾ This latter approach has the advantage that it permits systematic evaluation of shelter components; the results obtained can then be used to interpret the performance of any combination of these components forming a real shelter. A further advantage of this approach is that in experimental burns, data can be collected throughout the structure since any area can be assumed to be adjacent to the shelter.

In the experiments, therefore, no emphasis was placed on designating specific areas of the building as shelters and, in fact, only one shelter area was specified.

III. EXPERIMENTS

Three structures were reserved by the city of Waukesha for this study. Buildings 1 and 2 were of masonry and wood joist construction and selected portions of both were modified to simulate fire resistive construction. In both structures, major instrumentation was concentrated at or above the level of the initially ignited room. Building 3, also of masonry and wood joist construction, had a fire resistive portion, which isolated a part of the basement from the rest of the structure.

The following sections describe the structures, modifications made, locations of instruments, and experiments conducted in chronological order. Details of the instrumentation are given in Appendix A.

A. Building No. 1

Built around 1870, the structure was about 37 feet wide by 63 feet long by 36 feet high (three stories). The first floor was essentially on grade. The exterior walls were of native stone ranging from 27 inches thick at the ground to 21 inches thick at the third story, supported on a concrete footing. Some portions of the first floor were concrete slabs while other portions were of wood joist construction built over crawl spaces. The other floors were constructed of 2 inch x 12 inch joists on 16 inch centers, covered with a one-inch subfloor and oak flooring. The majority of interior walls were load bearing

brick, three courses thick on the first floor and two courses thick above the first floor. Small attic spaces existed at either end of the third floor but the ceiling was at roof level in the central portion and contained a large exhaust vent. Ceilings and walls were plastered. Window sash and frames, door frames, baseboards, and other trim pieces were hardwood.

Photographs of the building are shown in Figure 1 and a schematic cross-section of the building is shown in Figure 2. Two experiments were conducted in this building. In each, the fire was started in the first floor room labeled "fire origin" in Figure 2. This room and a portion of the adjacent one were lined with gypsum board and sheet metal to extend the period during which the fires resembled those which would occur in a fire resistive structure. Doors within the structure were arranged so that smoke and hot gases were channeled across the first floor and upward through a stairwell to the third floor level. A drop partition was placed in the middle first floor room to restrict the gases to a twelve-foot wide segment and this portion of the room received additional ceiling protective covering. Cross-hatching in Figure 2 indicates the portion of the building acting as a barrier to the smoke and gas spread. External openings were protected with sheet metal curtains extending downward to within several inches of the sills. In the first experiment all doors and windows (except



Figure 1. Building No. 1 (Waukesha, Wisconsin)

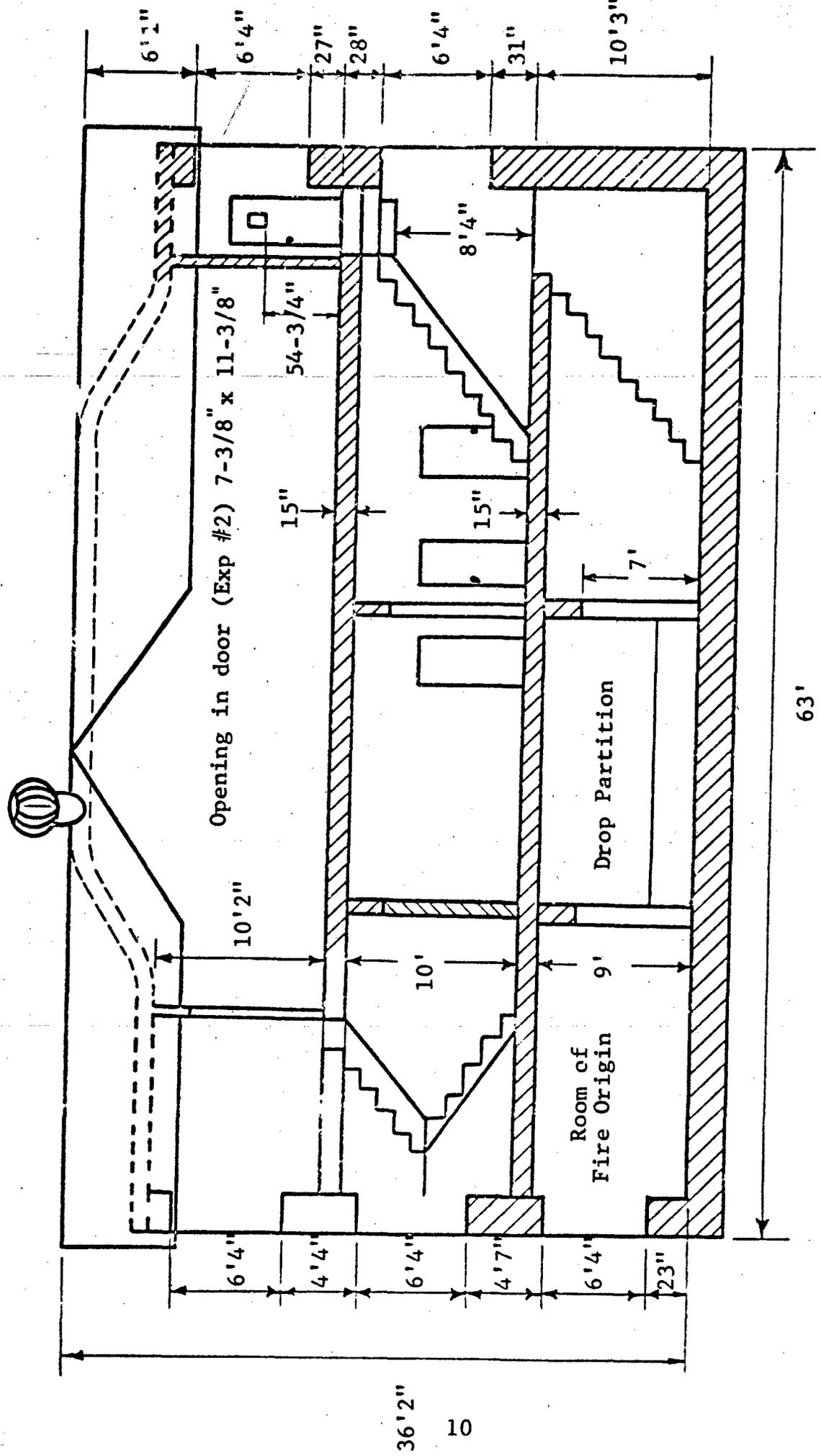


Figure 2. Schematic Cross Section of Building No. 1 (Waukesha, Wisconsin)

in the room of origin) were tightly closed. In the second experiment, a small opening was made in the door at the third floor to permit some bulk gas flow up the stairwell. These experiments can be considered similar to those conducted in "Operation School Burning"⁽³⁾ except that here a deliberate attempt was made to minimize the volume available for dilution of the fire gases and to maximize the pressure buildup in the stairwell.

Fuel loading in the room of origin consisted of a large wood crib (2 x 4 lumber) for each experiment which was weighed during the burn. (See Appendix A). The remainder of the structure was loaded with furniture to a typical residential condition in terms of the readily available fuels. No attempt was made to add those fuels which become available only in the later stages of the active fire such as closet contents and combustibles stored in dressers, chests and cabinets. Crib moisture content was between 9 and 12 per cent.

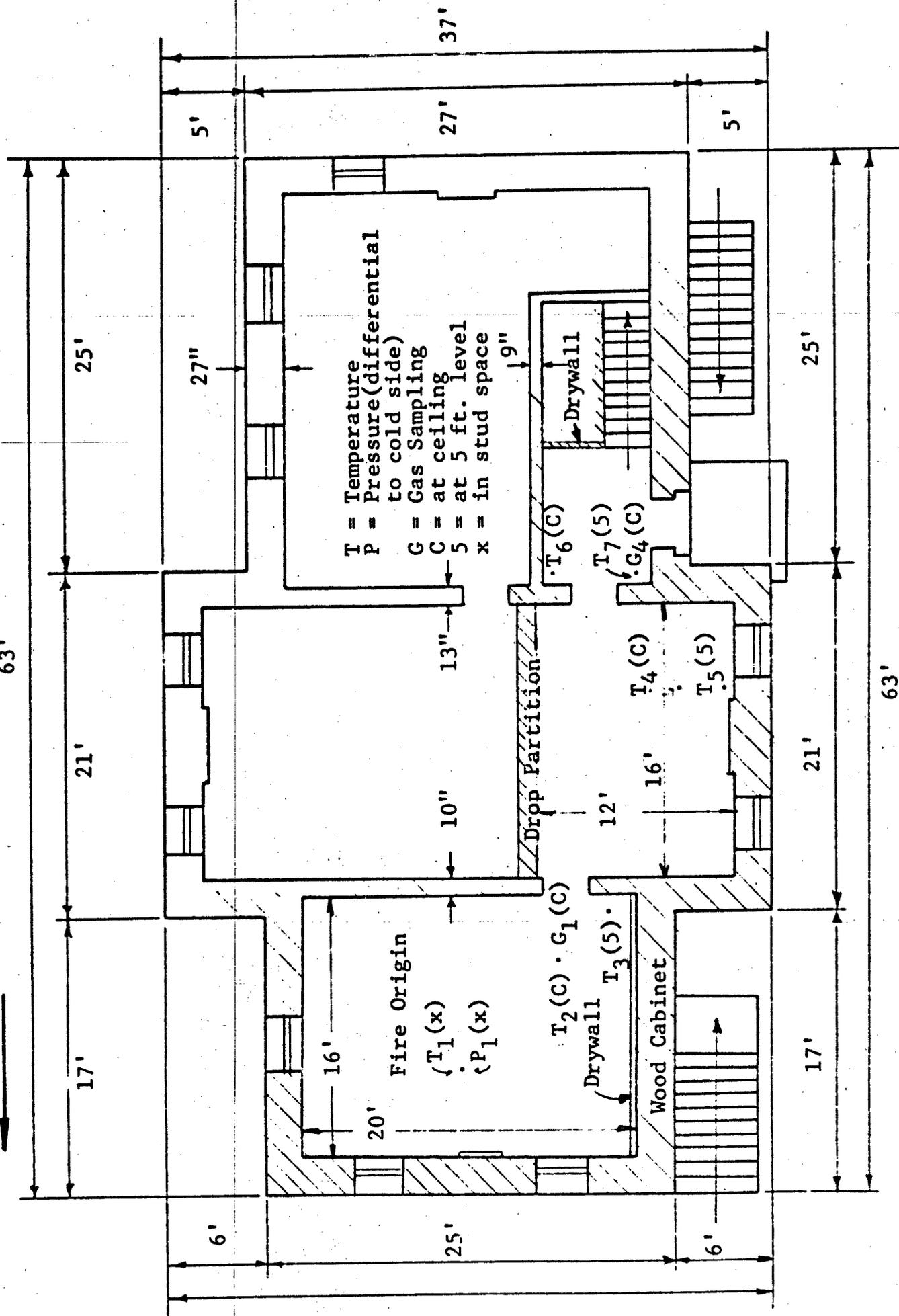
Temperatures, pressures, and CO and O₂ concentrations were monitored at various points along the path of the fire gases as shown in Figure 3. Gas flow was measured at the third floor door opening in Experiment No. 2. Weight losses of fuels in the room of origin were recorded as well as radiant heat fluxes from the openings.

B. Building No. 2

In all its essential features, Building No. 2 was the same as Building No. 1. A schematic cross section of this

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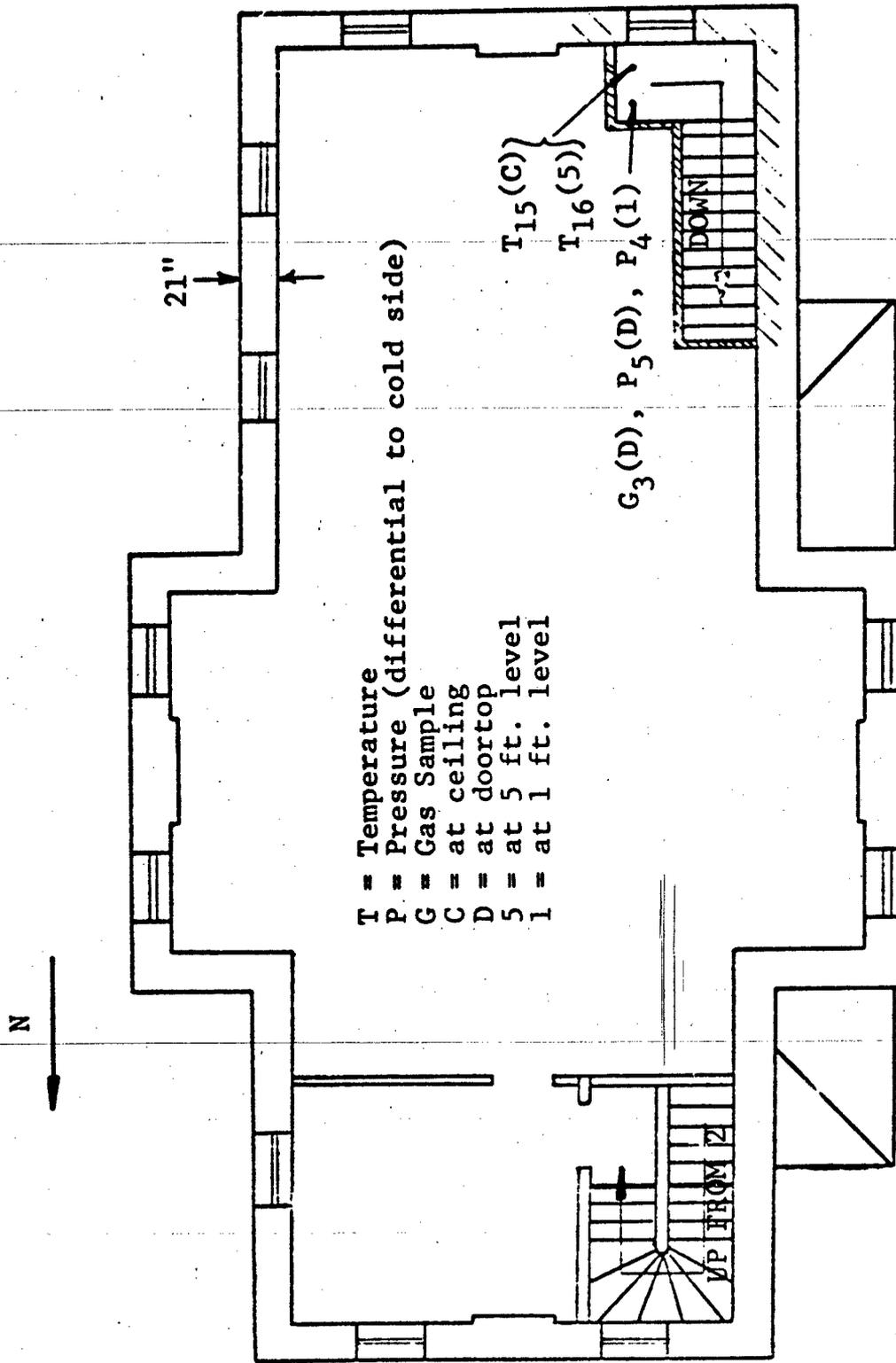


Figure 3C. Third Floor, Building No. 1 (Waukesha, Wisconsin)

building is shown in Figure 4. Cross hatching has been added to Figure 4 to indicate the portions of the building acting as a barrier to smoke and gas spread. One experiment was conducted in this building. The room of fire origin was on the second floor. Although it was not located above the first floor room used in Building No. 1, the path for smoke and gas spread and the volumes available along the path were quite similar. Again, the room of origin and a portion of the adjacent one were lined with gypsum board and sheet metal. Also, windows and doors were tightly closed (except in the room of origin) and protected where necessary.

Figure 5 shows the locations monitored for temperature, pressure and gas concentration. Weight losses of fuels in the room of origin and radiant flux from openings were also recorded.

Fuel loading of Building No. 2 was similar to that used in Building No. 1--a weighed crib in the room of origin and typical residential loading with real furnishings throughout the remainder of the structure. Moisture content of the crib varied from 9 to 12 per cent.

C. Building No. 3

This structure, also of masonry and wood joist construction, was two stories high with a large attic. It was about 90 x 160 feet and had apparently been two separate constructions. The exterior walls and a number of interior partitions were of brick. A series of exterior photographs are shown with a plan

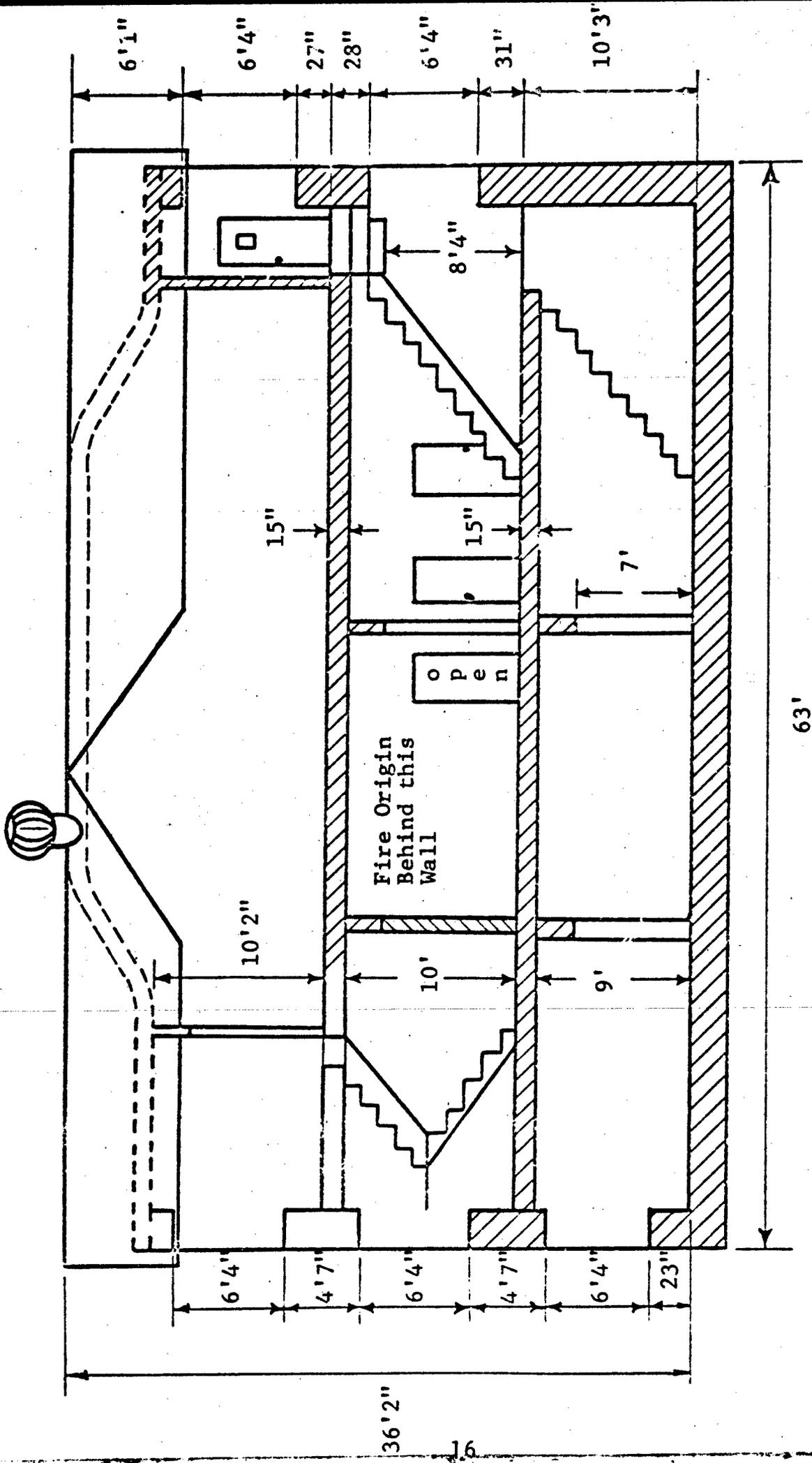


Figure 4. Schematic Cross Section of Building No. 2 (Waukesha, Wisconsin)

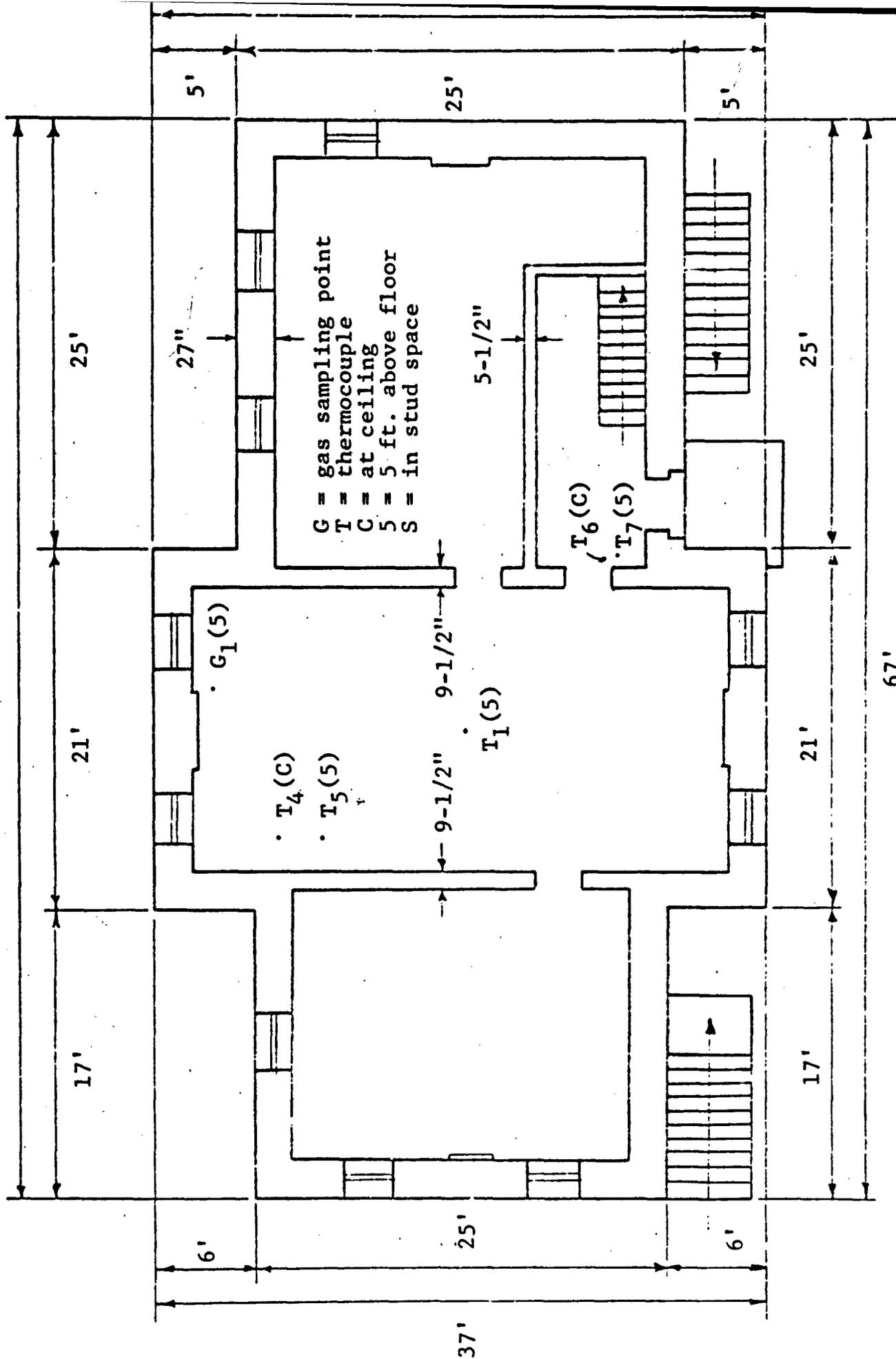


Figure 5A. First Floor, Building No. 2 (Waukesha, Wisconsin)

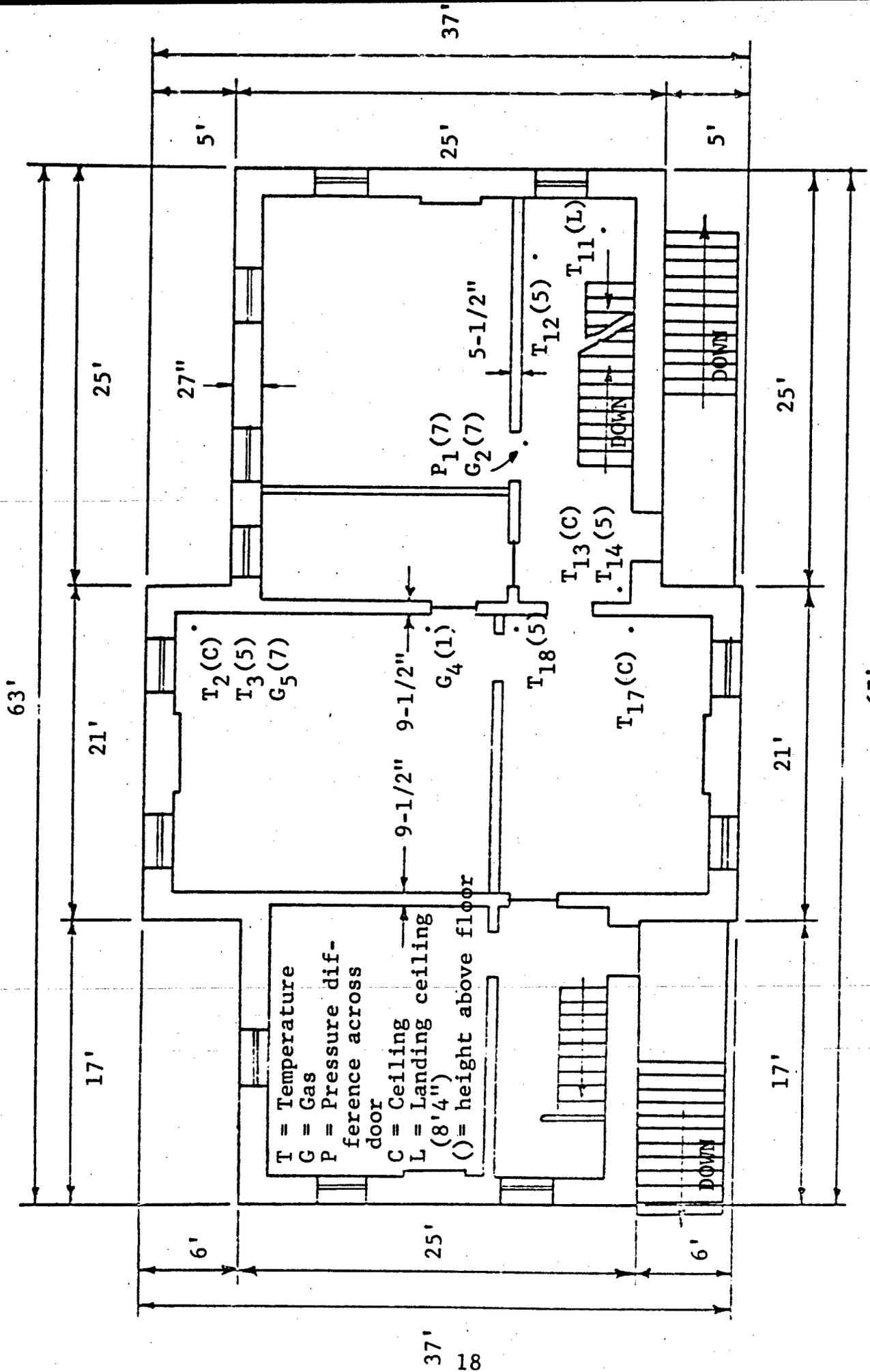


Figure 5B. Second Floor, Building No. 2 (Waukesha, Wisconsin)

G = Gas
 P = Pressure differential across door
 T = Temperature
 () = Height above 3rd floor-floor level
 C = Ceiling

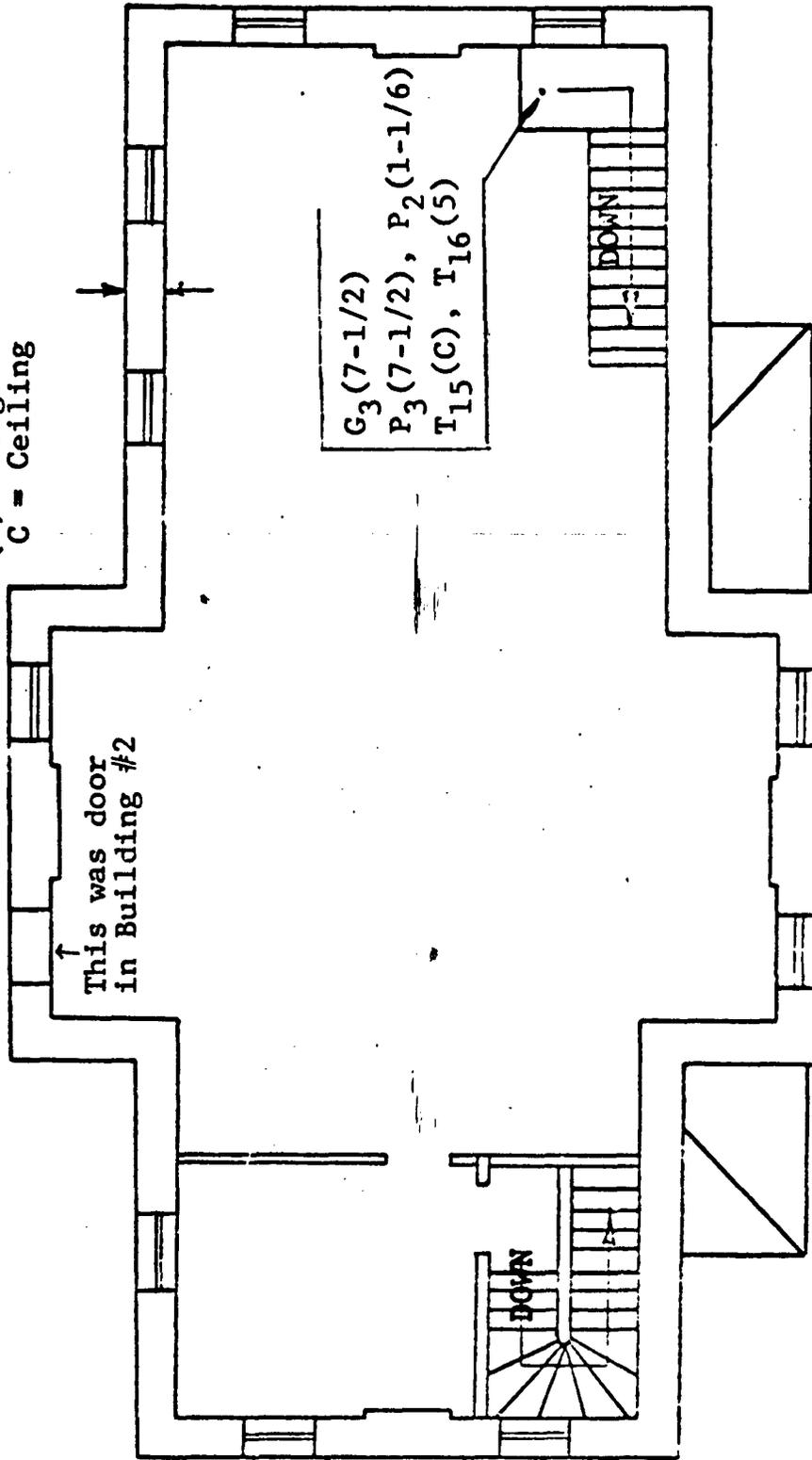


Figure 5C. Third Floor, Building No. 2 (Waukesha, Wisconsin)

drawing in Figure 6. The auxiliary structure shown in Figure 6 was a laundry building which ignited by radiation from Building No. 3 during the peak of the burn. This ignition was suppressed and burnout of the laundry did not occur.

Building No. 3 contained a dining hall (first floor) and auditorium (second floor) in the older portion (north) and had a large kitchen with cold storage vaults (first floor), music rooms and classrooms (second floor) in the newer portion (south). Ceilings and walls in the first and second stories were plastered. In addition, acoustical tile had been placed over the ceiling in the dining hall. Acoustical tile also had been added to the walls and ceilings of a series of small rooms built into the south end of the second story. Figure 7 shows the floor plans for the basement and each story. It might be noted that in addition to some interior brick load bearing walls, cast iron columns were used in the dining hall to support steel beams carrying the load of the second floor auditorium. The auditorium ceiling contained beams which were incorporated into a truss arrangement in the attic as shown in Figure 8. Because of the large room area and volume afforded by the dining hall (60 x 90 x 18 feet high) it was used to examine the minimum water requirement for extinguishment of this size room fire. Upon completion of the extinguishment experiments, the fire was allowed to rekindle and spread throughout the structure.

The basement area under the newer portion (south) had a poured concrete ceiling and could be

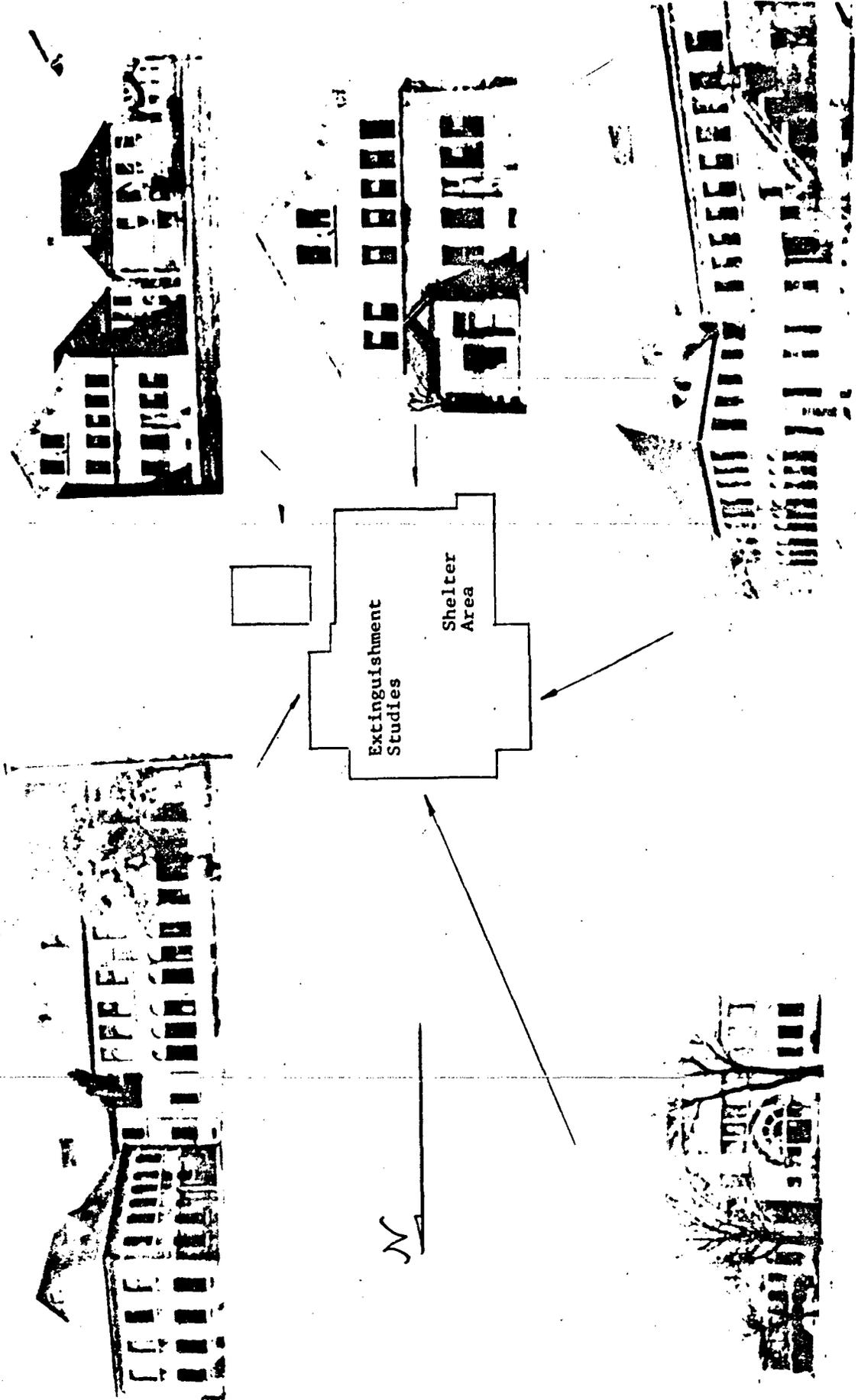
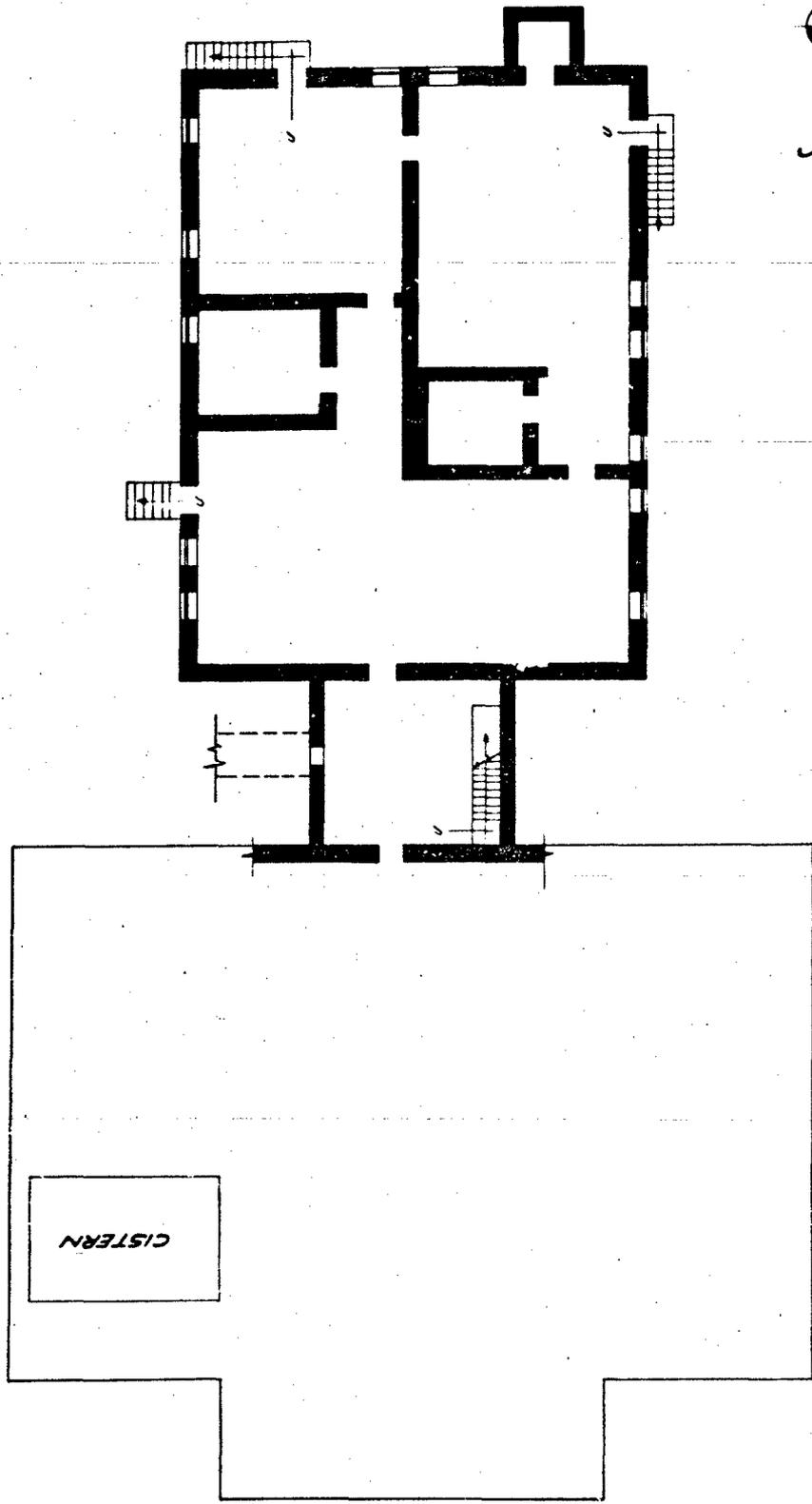


Figure 6. Photographs of Building No. 3



SCALE IN FEET

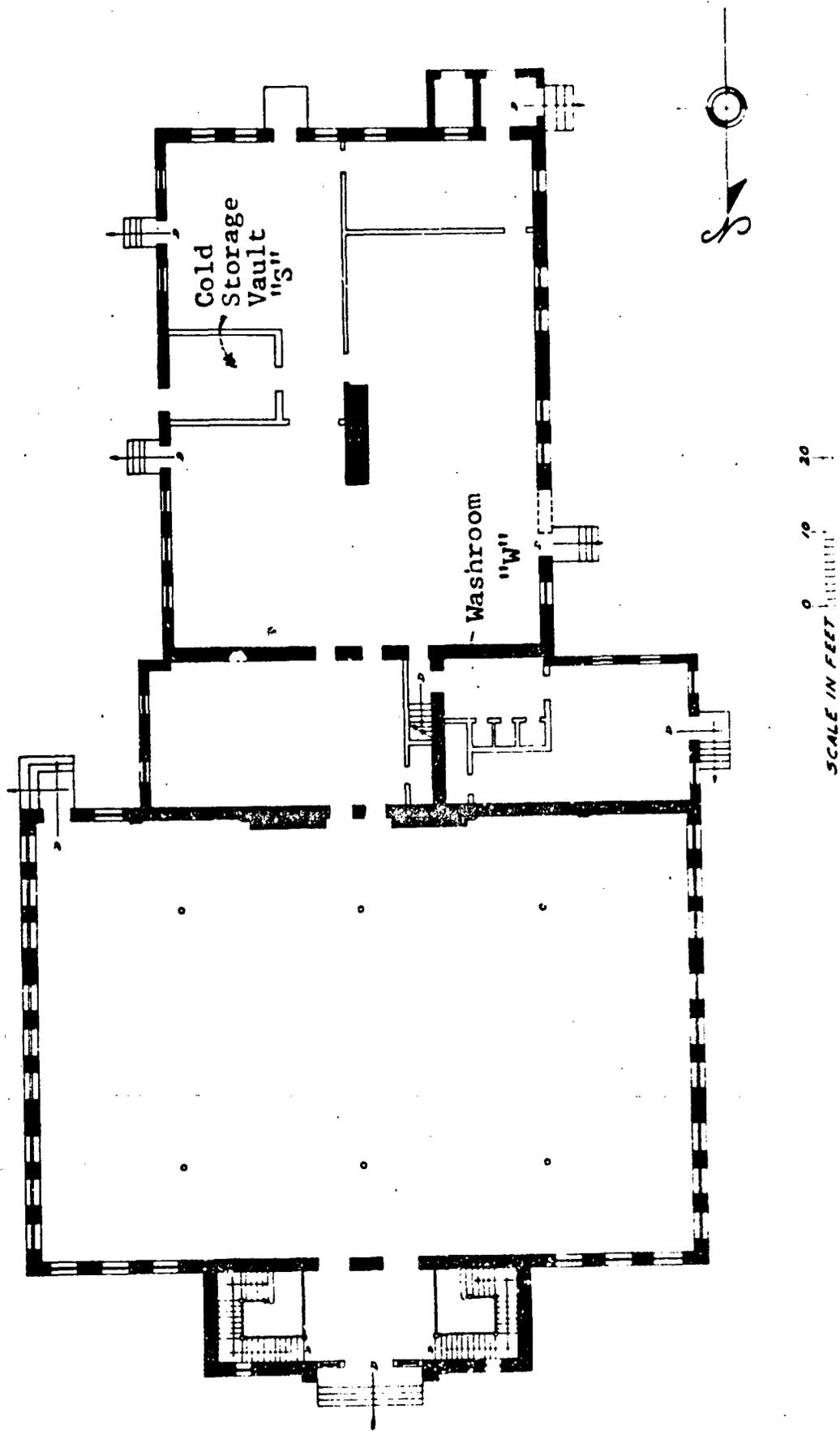
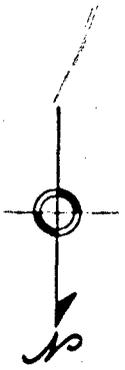
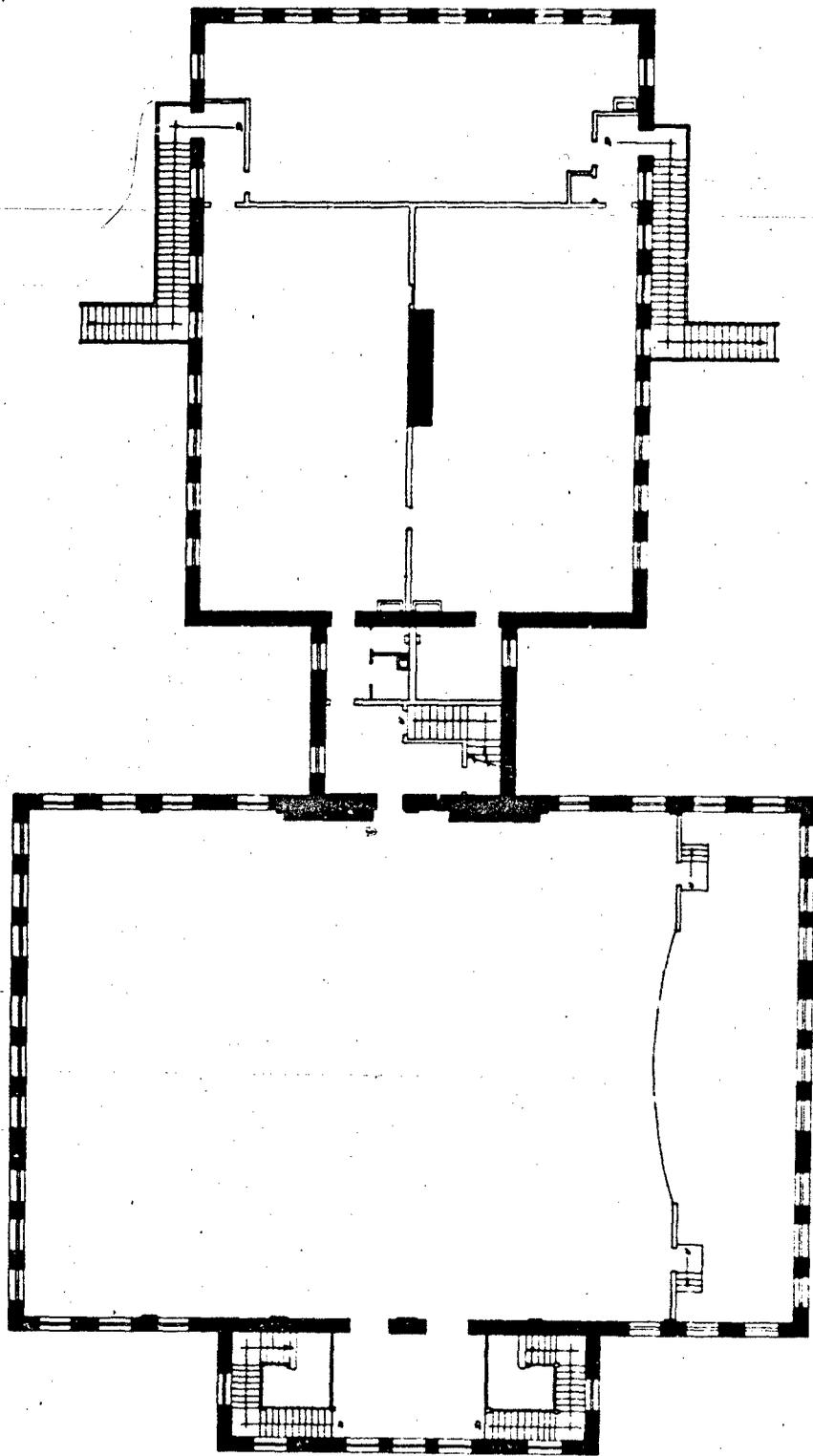


Figure 7b. First Floor Plan, Building No. 3



SCALE IN FEET

A horizontal scale bar with vertical tick marks. The bar is divided into three equal segments. The first segment is labeled '0' at the left end and '10' at the right end. The second segment is labeled '20' at its right end. The text 'SCALE IN FEET' is written vertically below the bar.

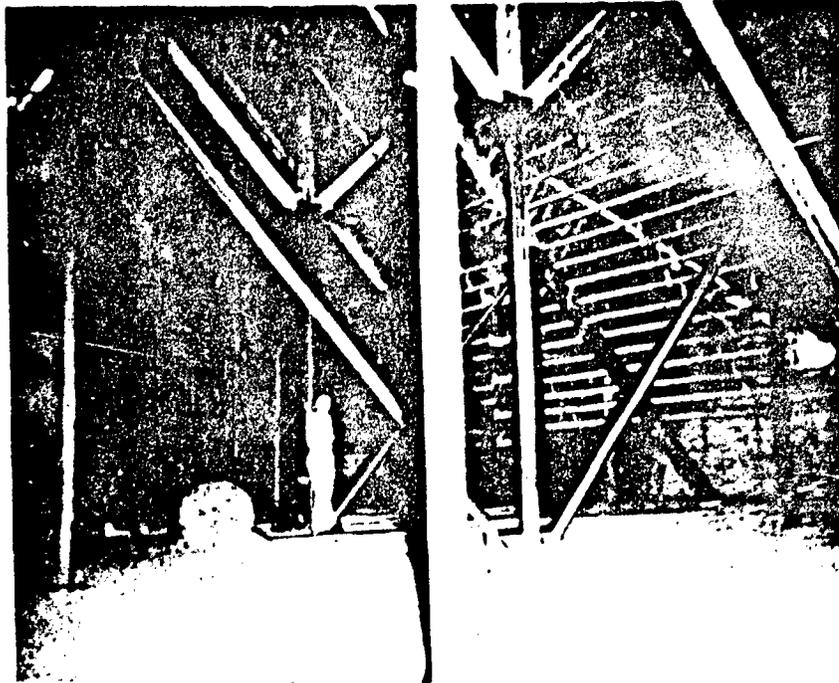


Figure 8a. North Attic (Over Auditorium and Dining Hall)

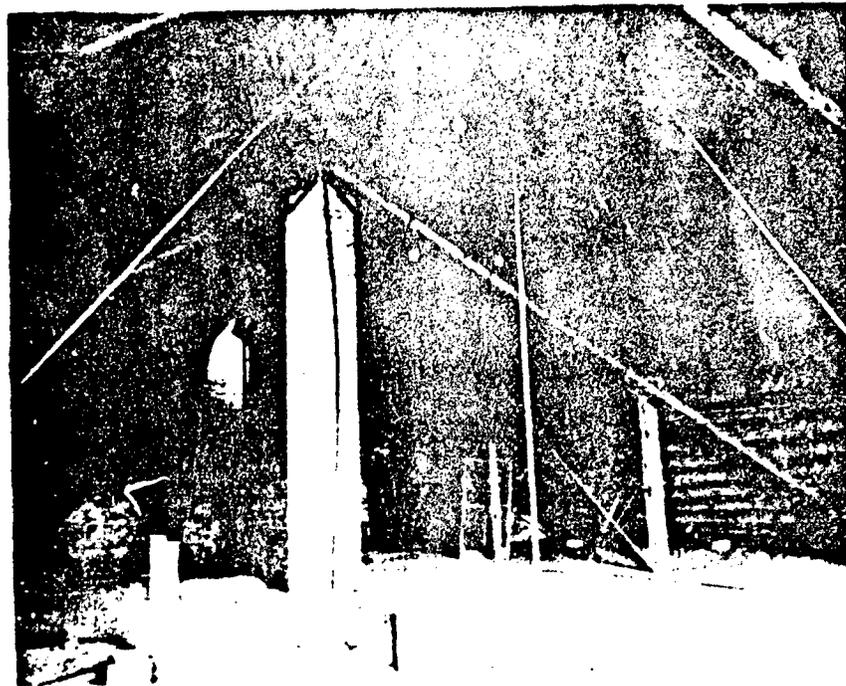


Figure 8b. South Attic (Chimney shown forms back wall of basement shelter)

Figure 8. Photographs of Attic Spaces
(Building No. 3, Waukesha, Wisconsin)

considered fire resistive. Conditions in and around this fire resistive basement area were monitored during the structural burnout. Details of the basement are included as Figure 9. The interior room labeled "shelter" was analyzed by M. P. Gronbeck, a qualified shelter analyst. Excerpts from his report follow:

REPORT ON
SIMULATED FALLOUT SHELTER
WAUKESHA BURN

Waukesha, Wisconsin
April-May, 1965

The Waukesha burn coincidentally provided a fallout shelter capability in one of the structures involved in the project. This shelter met the requirements of OCD for fallout shelters as set forth in publications on the current state of the art of shelter analysis.

Factors which guided the selection of the shelter site were (in order of importance):

1. place in building affording greatest mass barrier (thickness x mass) to protect the inhabitants from fallout radiation
2. place requiring least modification to make it an acceptable shelter consistent with OCD requirements
3. place providing for access of instrumentation.

Analysis of Shelter Selected

The protection of the shelter was calculated as follows by use of the Protection Factor Estimator. The protection factor P_f was approximately 100. (For layout and dimensions of the shelter, see Figure 9.)

A review of the plans will show that a large part of the basement area might be used as a shelter with some

modification of the window openings. This would consist of closing the openings with masonry to provide for a mass thickness of one foot of concrete. In this case, an initial test of a shelter under fire conditions, it was felt that such an undertaking was not warranted, and only a portion of the basement was selected for the test. (See plans of the basement area.)

For the purpose of this test the use of the protection estimator was assumed to give results of sufficient accuracy. The layout was without any structural complications calling for greater refinement of calculations.

The windows opposite the shelter were noted (see Figure 10) but they were assumed to have been filled with masonry. The contribution from this source would consist of skyshine with some ground direct, both quite insignificant in this case in considering the geometry of the shelter layout.

In order to approximate a fire resistant door at the entrance to the shelter proper, the wooden door in place was covered with 3/8" gypsum sheetrock. This arrangement provided for 3/4-hour fire resistance.

Instrumentation of the shelter was completed by the engineers and technicians of IIT Research Institute, who also cared for the appraisal of the data assimilated during the burn.

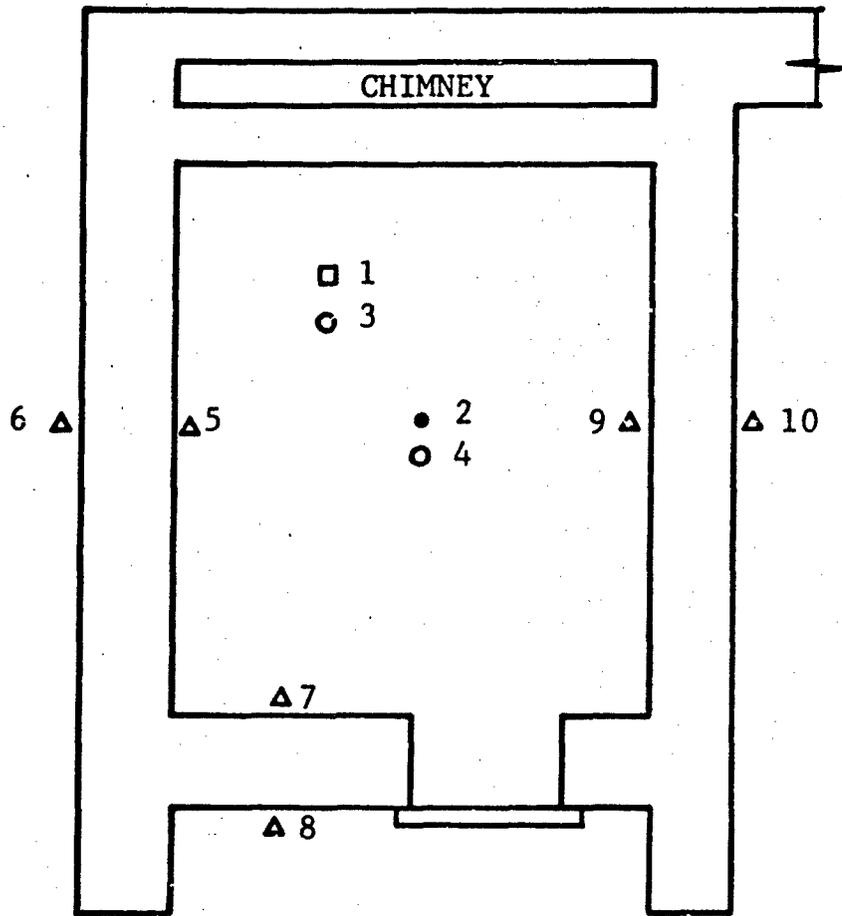
The Waukesha burn effectively pointed up that buildings which are to be burned may have inherent shelter potential which may serve as test sites in order to gain knowledge of shelter susceptibility in a fire situation. This knowledge is vital to the national fallout shelter plan."

As mentioned earlier in this section, the fire was started in the dining hall and a series of extinguishment experiments was conducted. The details of these experiments are contained in Appendix B. Upon completion of the extinguishment experiments the fire was allowed to rekindle and spread throughout the structure. During structural burnout, data were accumulated in and around the designated shelter area. Measurements included temperatures, pressure differences, carbon monoxide and oxygen concentrations. Locations of instrumentation are shown in Figures 11 and 12. In addition, radiation measurements were taken at several locations on the



Note - Basement windows were covered with sheet metal or plaster board to simulate a condition in which windows are bricked-over. The coverings remained intact throughout structural burnout.

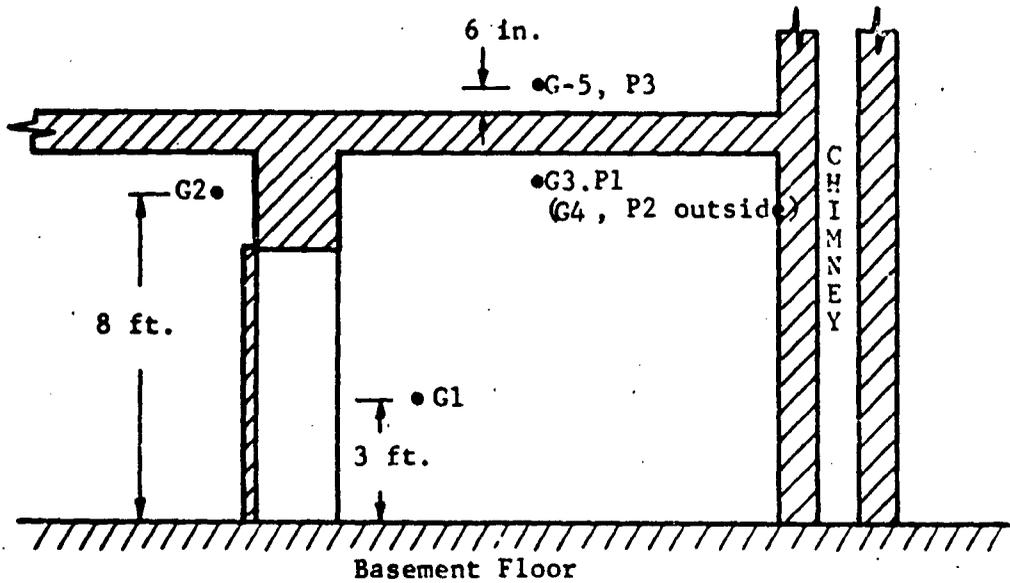
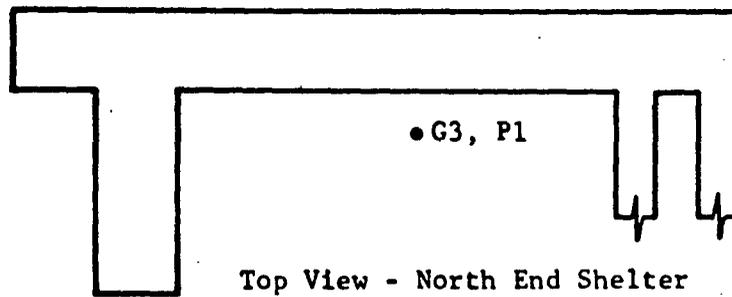
Figure 10. Windows in Basement Area Near Shelter Building No. 3, Waukesha, Wisconsin



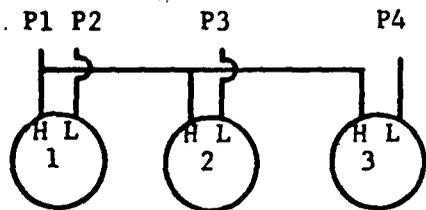
Code: Δ = 5 ft. level
 \bullet = 2" below ceiling
 \square = attached to ceiling
 \circ = 2" above first floor

Figure 11. Temperature Measurement in or near Shelter Area - Building #3 (Waukesha, Wisconsin)

• G4, P2 (8 ft level)



Pressure Gauge Attachment for Building No. 3



(Note: P4 is in open field about 40 Ft west of building)

Figure 12. Locations of Gas Sampling Points and Pressure Taps in Building #3 (Waukesha, Wisconsin)

laundry building as shown in Figure 13 as well as at a small shed located 70 feet west of the structure.

Contents fire loading was not added to major portions of Building 3. The dining hall was loaded for the extinguishment experiments. However, the remainder of the structure contained built-in cabinetry and wood partitioning which combined with the structural combustibles was estimated to reasonably approximate the contents load of a totally fire resistive structure.

IV. RESULTS

Presentation of the results of fire experiments in simple, concise form is difficult since a small amount is usually learned about each of many interplaying parameters. This problem is further complicated here because the approach to study in Building No. 3 was different from that for Building 1 and 2. To make this presentation more orderly, therefore, the results have been grouped according to each parameter under investigation and then examined for each study approach as applicable.

A. The Fires

1. Crib Fires - Buildings No. 1 and 2

As mentioned earlier, Buildings 1 and 2 were modified to extend the period in which each fire was contained by the room of origin and thus resembled fire in a fire resistive



Radiometer #1
facing north

Radiometer #2
facing west

Radiometer #3
facing west

Figure 13. Radiometers, Burn 3 (Waukesha, Wisconsin)

structure. Wood cribs were selected for the fuel as they represent a reproducible fire load which has a fairly constant, easily monitored burning rate. Ventilation of the fires was restricted to insure that CO generation and O₂ depletion were sufficient to be readily monitored. Gas compositions in corridors and stairwells can be inferred for fires with different outputs by relating them to the outputs of the room of fire origin.

The cribs used in Buildings 1 and 2 consisted of 2" x 4" lumber placed on a weighing platform (described in Appendix A). Each crib consisted of 450 lineal feet (or 600 pounds) of lumber placed in alternating rows of 10 ft. lengths on edge and 5 ft. lengths laid flat as shown below.

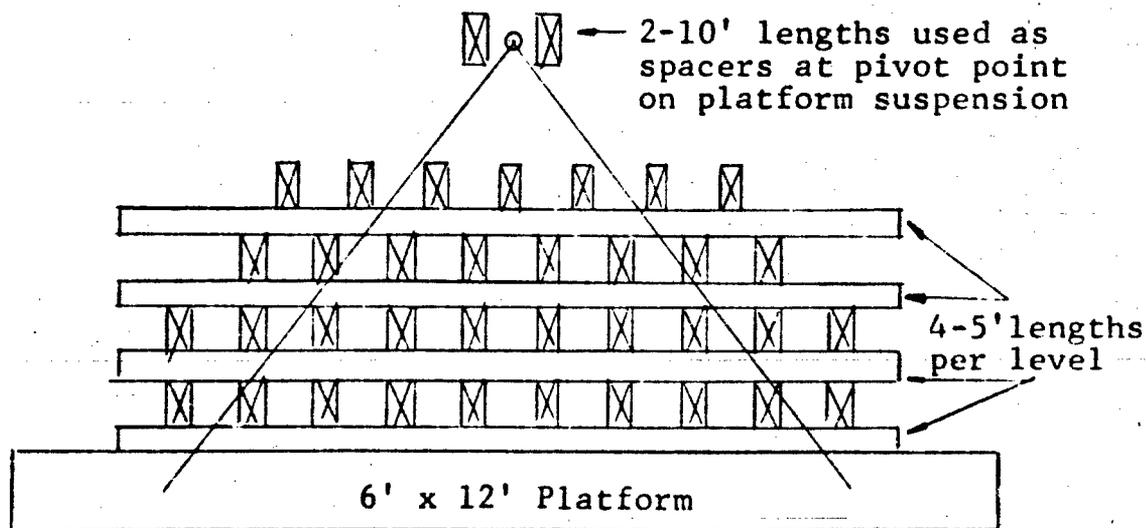


Figure 14. Crib Arrangement for Buildings 1 and 2

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Several layers of paper wipers were placed on the platform before assembling the cribs. Application of JP-4 fuel to the paper just prior to ignition produced rapid involvement of the entire loading.

The weight loss of crib number 1 from Building 1 is shown in Figure 15. The figure shows that a constant burning rate of 12.8 lbs/min. was achieved about 4 minutes after ignition and lasted at least 26 minutes. This represents a heat release of approximately 100,000 Btu/min. Ceiling temperatures near the doorway averaged about 1000°F during the period of constant burning rate.

Crib 2 burned quite differently from Crib 1. As shown in Figure 16, the burning rate during the first five or six minutes of active burning was 33 lbs/min. It then decreased somewhat so that the average rate was 25 lbs/min between the 4th and 14th minutes. These burning rates represent heat releases of about 264,000 Btu/min and 200,000 Btu/min respectively. Ceiling temperatures at the door averaged about 1300°F during the peak burning period but then dropped rapidly resulting in an average over the first 30 minutes of about 1000°F (similar to Burn 1). This rather drastic change of burning behavior can only be attributed to the vent opened at the top of the stairwell for Burn No. 2. The additional air this venting permitted to reach the fire (see Figure 17) would not account for the increased burning rate on a stoichiometric basis. However, the location of the crib and the window opening

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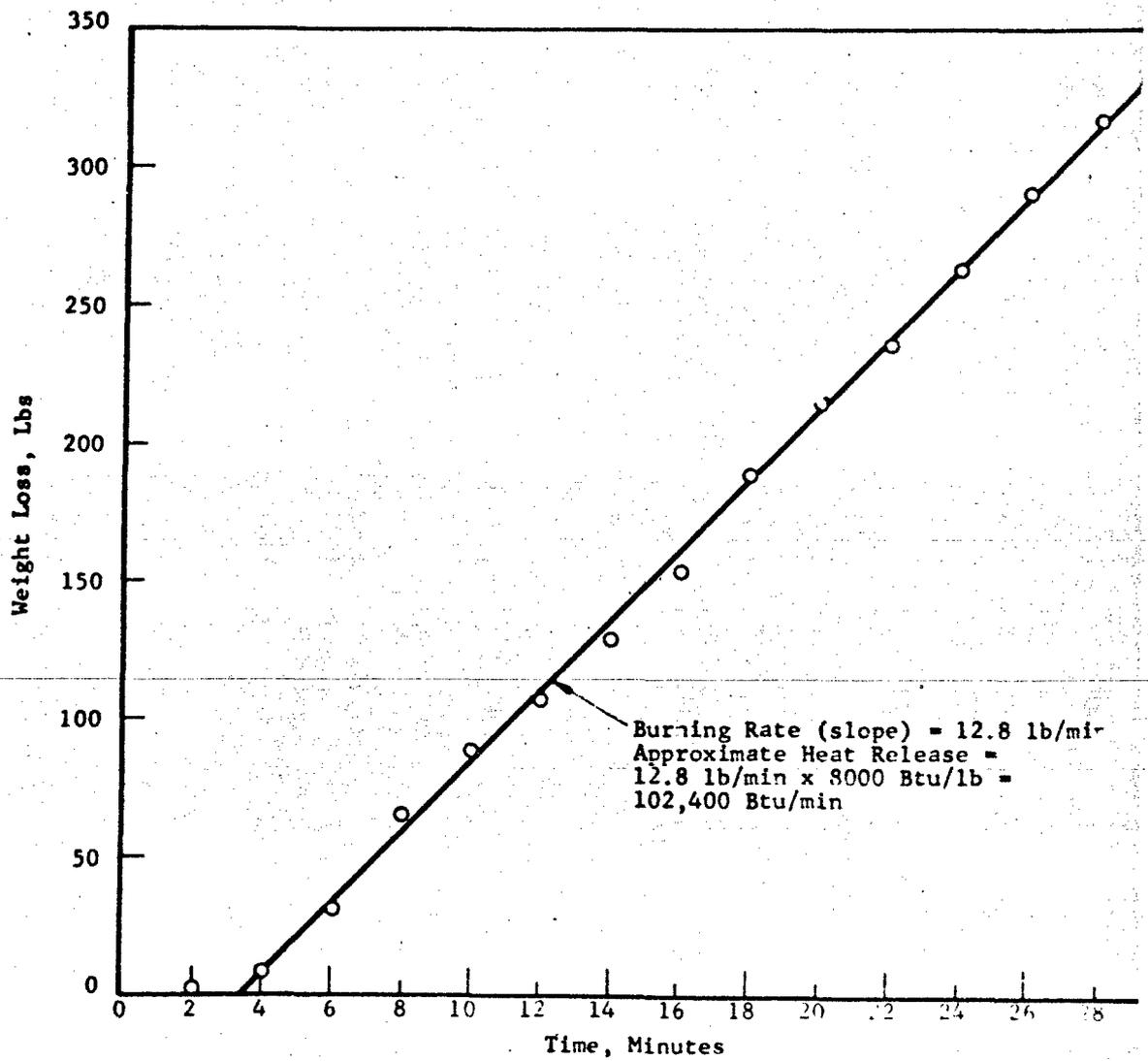


Figure 15. Burning Rate of Crib No. 1, Building No. 1

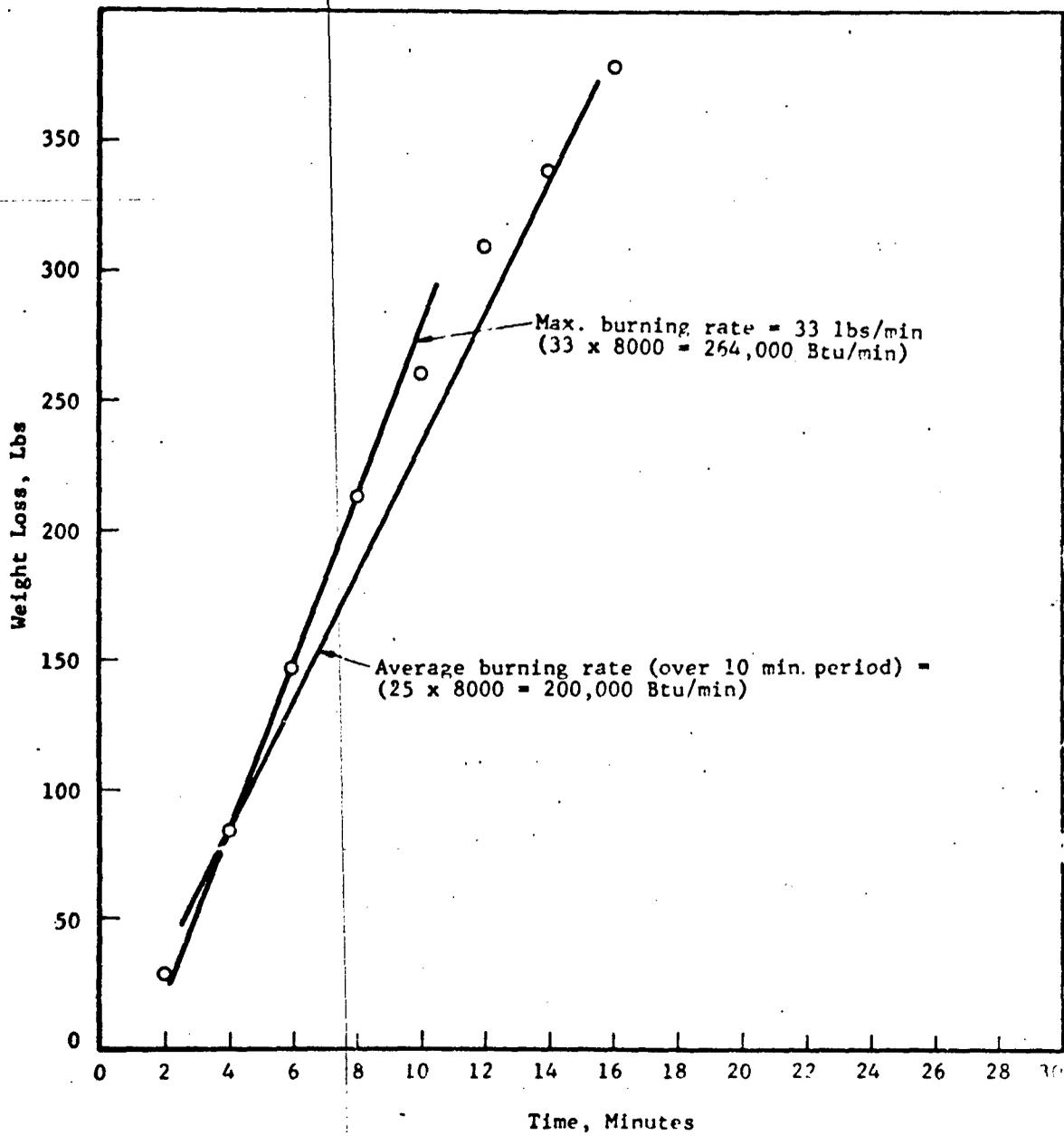


Figure 16. Burning Rate of Crib No. 2, Building No. 1

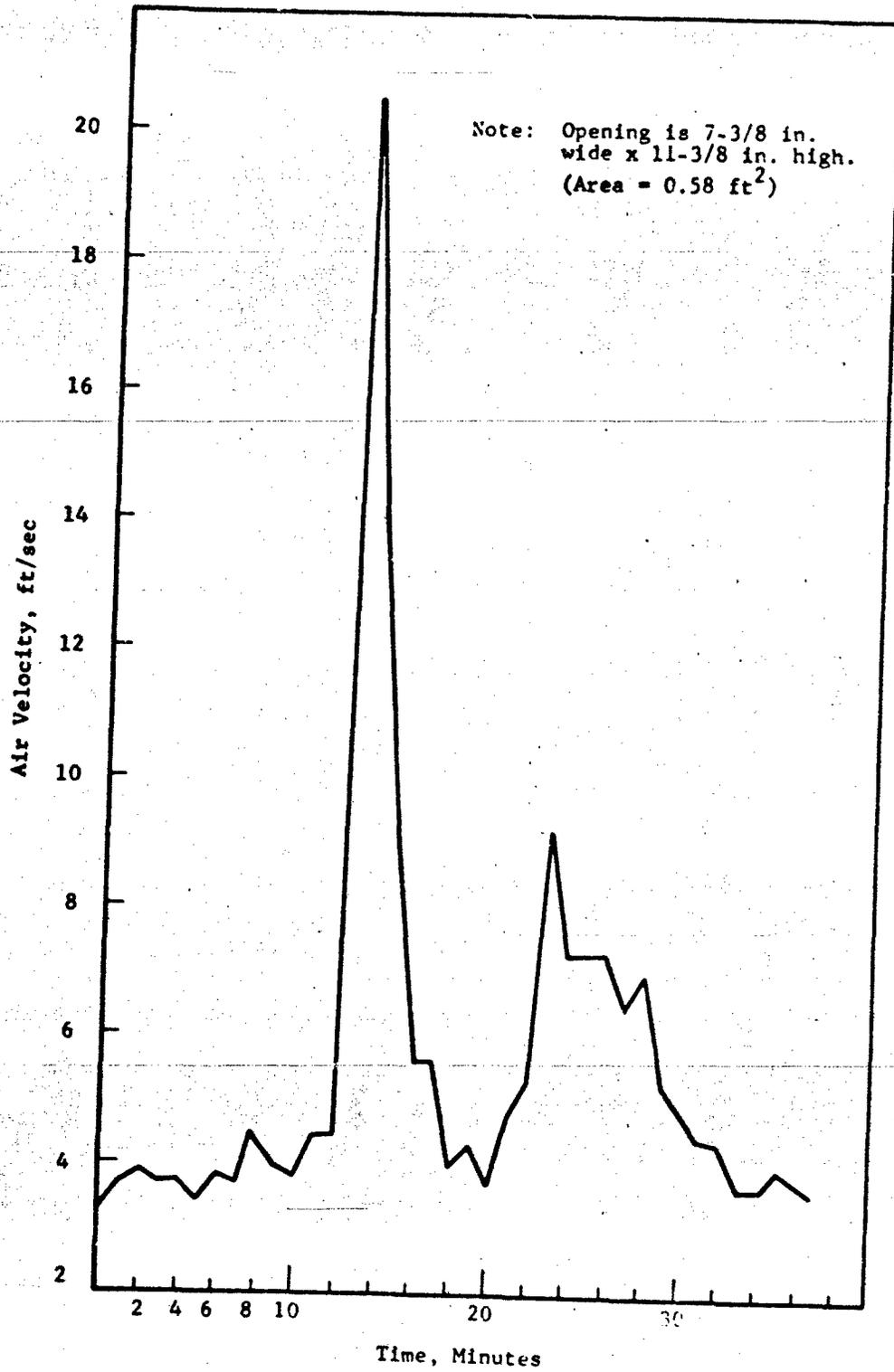


Figure 17. Air Flow from Stairwell Vent Experiment 2, Building 1

was such that the air flow tended to be through the crib thus overcoming, to a significant degree, the natural restriction of the crib matrix to self-induced air flow and the high burning rate was achieved until the fuel supply decreased.

That such was the case can be verified to some extent in the following manner. Thomas⁽⁴⁾ gives a correlation for burning rates of ventilation-controlled fires as

$$R = 0.678 A \sqrt{h}$$

where R = burning rate (lb/min)

A = area of opening (ft²)

h = height of opening (ft.)

The constant, 0.678, was found by Waterman et al.⁽⁵⁾ to be lower than values measured using furnished model rooms. They suggest a maximum value of 1.5 for distributed fuels (as opposed to cribs). The lower value can be attributed to the additional air flow restriction of most cribs even when the general level of burning rate is being controlled by the room openings. A relation for estimating the maximum burning rate of wood in well-ventilated fires was derived from examination of numerous standard fire test results on combustibles⁽⁶⁾ as:

$$R = 0.09 A_s$$

where A_s = fuel surface (ft²)

The burning rate calculated according to Thomas' equation for Burn 1 (one opening 33" wide x 31" high and two openings 33" wide x 12" high) is 11.4 lb/min (the measured rate was

12.8 lb/min). For the second burn, calculation according to the equation for the well ventilated fire gives a maximum rate of 35.6 lb/min (the measured rate was 33 lb/min).

The crib burning rate for Building No. 2 is shown in Figure 18. The decrease in burning rate near the start is unexplained. That it did in fact occur is verified by the temperature records, as is the subsequent increase in the burning rate. The burn room was on the downwind side of this structure and perhaps this may have disturbed the flow pattern at the openings. The average rate, 12.5 lb/min, compares well with that which is calculated for two openings, each 33" wide x 30-1/2" high, i.e., 15.1 lb/min.

2. Fire History of Building No. 3

Building No. 3 contained the specified shelter area. Since it is of interest to compare the data collected in and around the shelter with the status of the fire and condition of the rest of the building, a brief summary of the fire history is presented below as Table I. The comments have been keyed to Figure 19, a plan view of Building 3 and the adjacent laundry building.

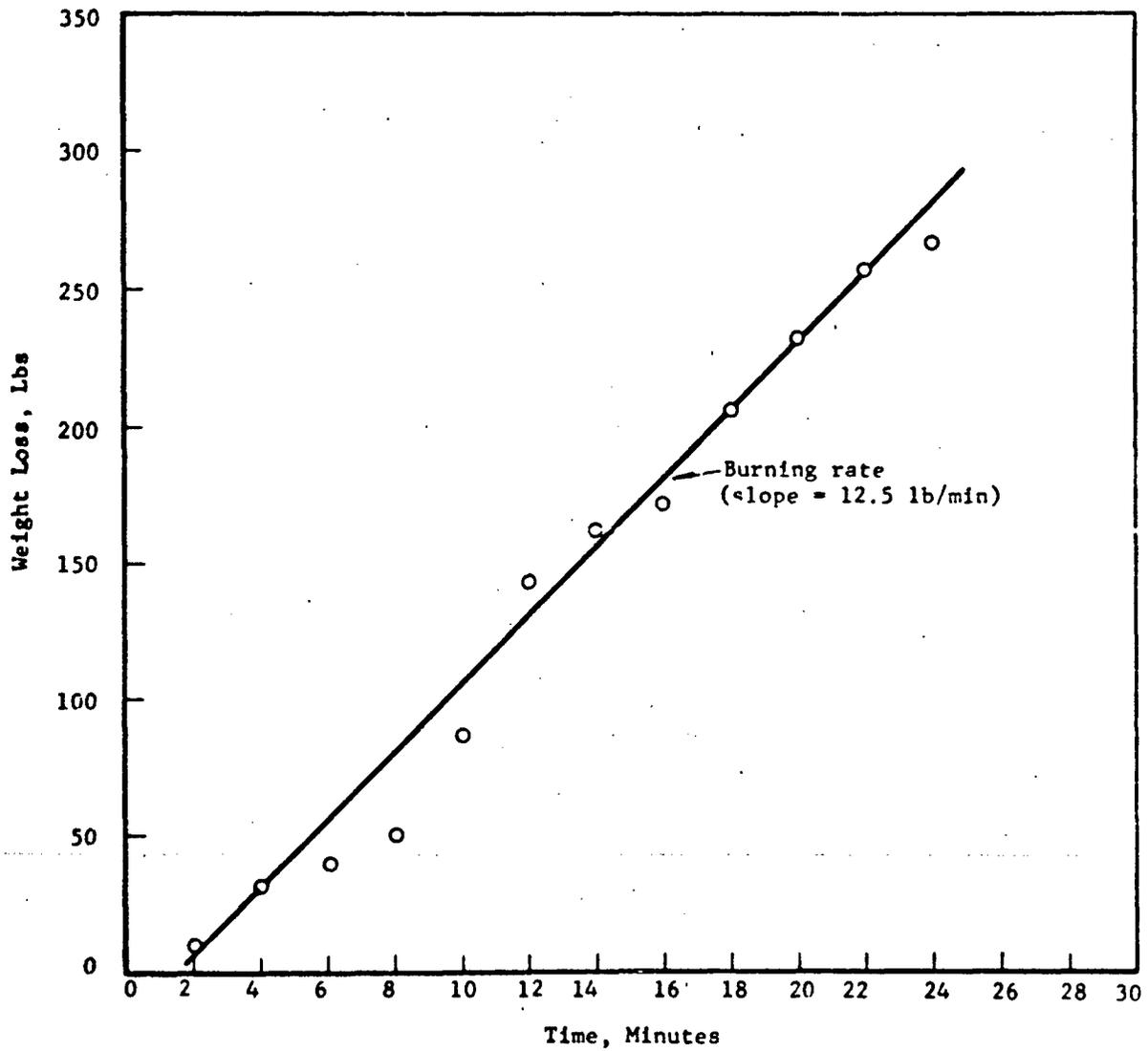


Figure 18. Burning Rate of Crib, Building No. 2

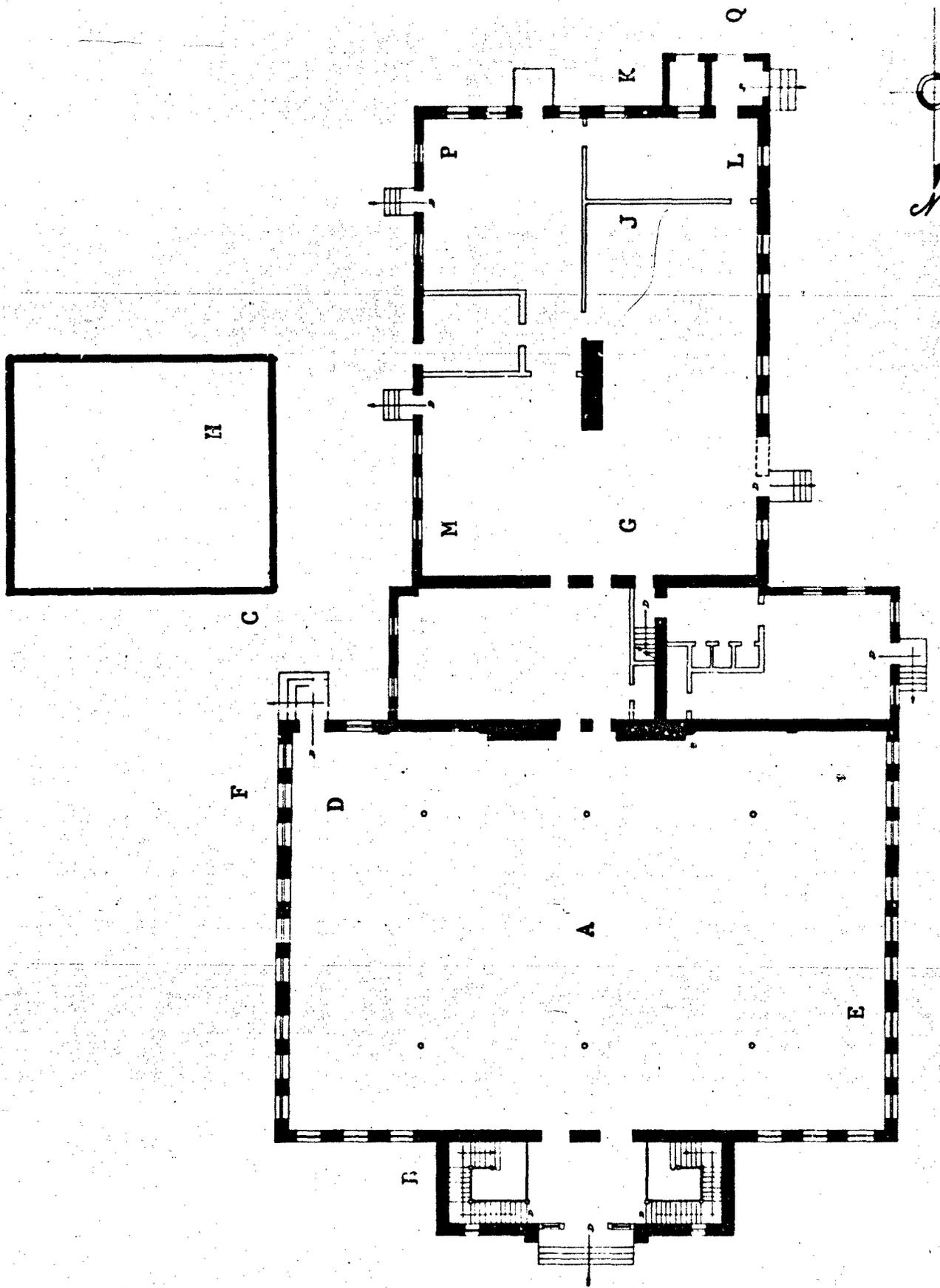


TABLE I
FIRE HISTORY, BUILDING 3

Time	Event
10:57	Multiple ignition of dining hall (A) 1st floor, wind SW, 7 mph
11:01-11:25	Extinguishment experiments, dining hall
11:25--	Rapid involvement of 2nd floor auditorium and north attic (A) (note: stage on 2nd floor had direct openings into attic spaces) violent flames at windows
11:32	Dense gray smoke from north end of roof (B)
11:37	Roof penetration (B), north end of north attic
11:43	2nd floor laundry window and screen frame smoking (C), wood is slightly rotten, heavily painted
11:44	North attic roof penetration (D) and (E)
11:50	Major collapse of north roof, flames appear on upper frame of laundry window (C)
11:52	Partial collapse of east wall, 2nd floor auditorium (F) (The fire spread very slowly upwind within the structure on the 2nd floor, slightly faster in the attic. Protection added to the 1st floor to prevent premature spread during the extinguishment experiments proved very effective and direct 1st floor spread did not occur.)
12:12	Roof penetration of south attic (G), ignition of sill and frame of window in laundry dormer (H) apparently by a brand
12:14	Roof collapse at G, glowing penetration to interior of laundry window (C), spasmodic flaming of paint on inside of frame

Figure 19. Plan View, Building No. 3

12:15	Sustained flaming on inside frame (C)
12:23	South attic roof burning back to J. During this burning, the cement asbestor shingles (used on south attic and the connecting roof) exploded violently scattering pieces in all directions
12:27	All of south attic roof involved
12:28	Flames visible on second floor at K
12:30	Active flaming of dormer window (H) reinforced by burning south roof
12:35	flashover of second floor at L
12:39	All of second floor actively burning
12:40	Major ceiling collapse, 2nd floor
12:48	Debris falls into basement stairwell at L (window screen from 2nd floor)
1:14	Partial ceiling collapse at M, 1st floor
1:17	Debris ignites boxes in opening on 1st floor at N
1:18	Flames active at M, 1st floor
1:28	1st floor window opened at L
1:36	Further ceiling collapse at M, 1st floor
1:37	Ceiling collapse at P, 1st floor
1:38	Ceiling collapse at K, 1st floor
2:15	Basement door penetrated (M) (no fuel load inside at this point)
3:30	Active burning of entry at Q (includes dumb-waiter to basement) Debris fell near this entry but did not cause ignition, small amount of fuel added by personnel
4:09	Flames on basement ceiling at P. This corner of basement ceiling was not fire resistive. (2 x 12 on 16" centers)

4:48 Partial basement ceiling collapse at P
4:56 Further basement ceiling collapse at P

B. Temperatures

1. Buildings 1 and 2

Temperatures from the experiments in Buildings 1 and 2 appear as Figures 20, 21 and 22. All data points are not shown; sufficient points were extracted from the records to define general levels, peaks and major points of inflection. It may be noted that thermocouples 6, 7, 11, 12, 13, 14, 15 and 16 (see Figures 3A, 5B, and 5C for thermocouple positions) each have the same location in both buildings. Thermocouples 2 and 3 each have the same location relative to the fire in each building. Thermocouples 17 and 18 in Building 2 were positioned relative to the fire in nearly the same manner as were Thermocouples 4 and 5 in Building 1. The ceiling temperatures (Thermocouple 2) monitored in the area of origin were not over the fire but near the doorway where gases leave the room to spread through the structure.

A number of observations can be made from the data shown in Figures 20, 21 and 22. First, the fires did last long enough to permit all monitored points to reach an essentially steady-state condition. For example, Figure 20 shows that temperatures at points furthest from the fire (13, 14, 15 and 16) were essentially constant shortly after the peak temperature

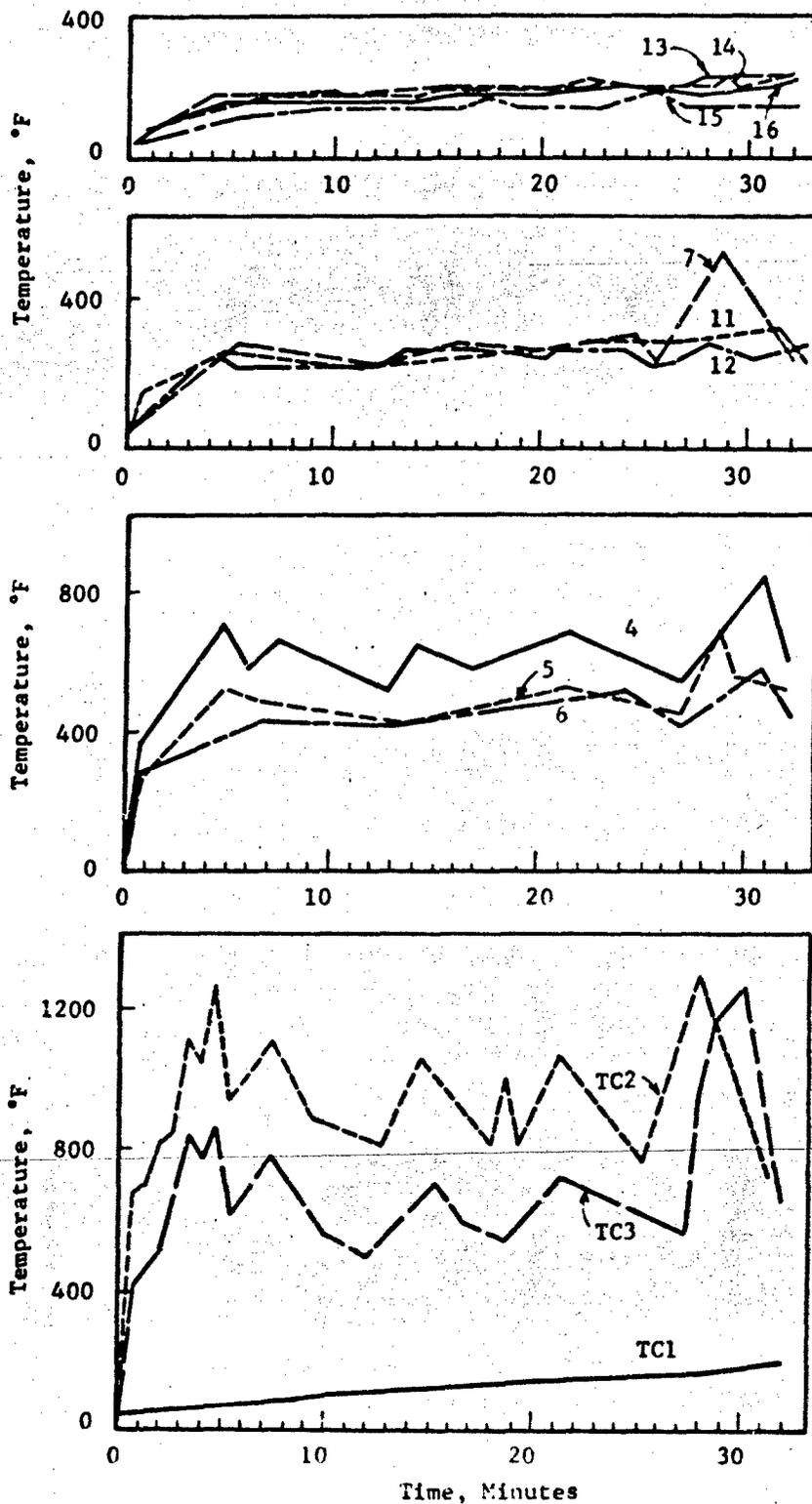


Figure 20. Temperatures, Building No. 1, Experiment No.

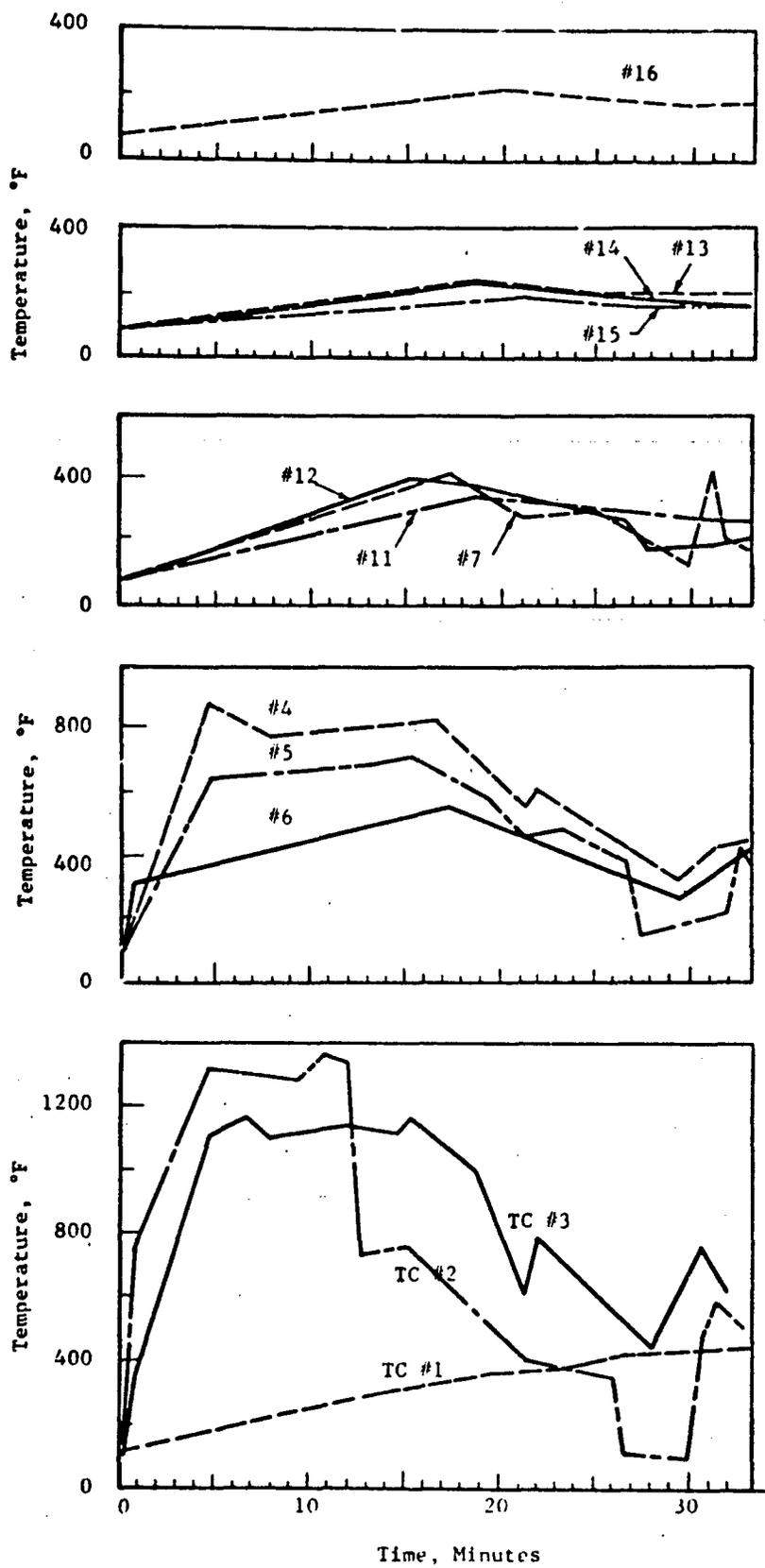


Figure 21. Building 1, Experiment 1

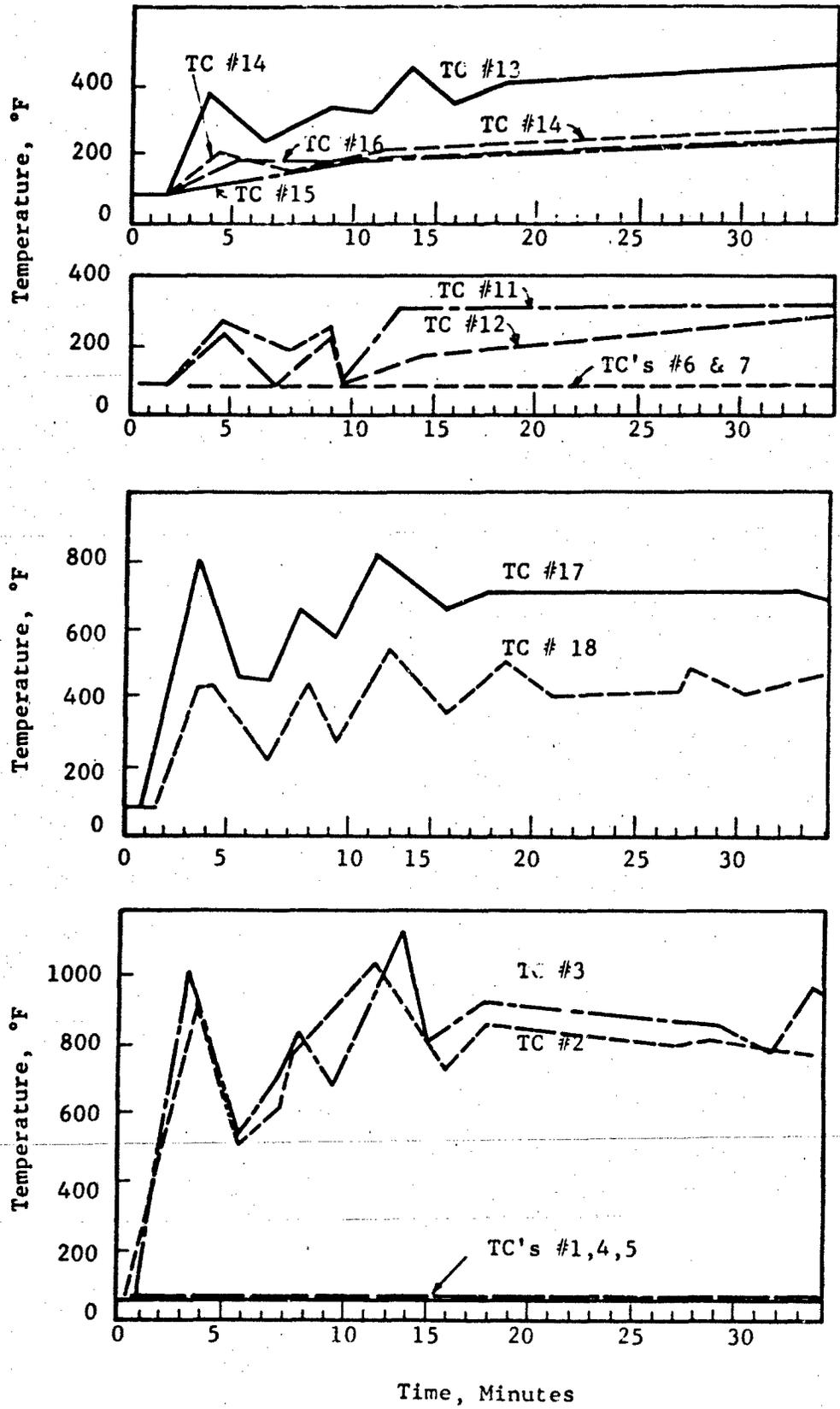


Figure 22. Temperatures, Building No. 2

was reached in the burn room. The temperature variations of the burn room, although damped with distance, can be seen to appear throughout the path with very little time lag.

The small vent placed in the stairwell for Experiment 2 had only a very slight effect on temperature levels at the top of the stairwell (Thermocouple 11). In Building 1, although the heat release rate was higher during the early part of Experiment 2, the temperature of the gases leaving the doorway was not much greater than in Experiment 1. It appears that the additional heat in Experiment 2 was largely absorbed by the walls and ceiling in the immediate fire area (see Thermocouple 1 placed in the stud space above fire). Gases reaching the top of the first stairway (Thermocouple 11) showed little timewise temperature variation compared with those observed in the burn room. Damping of these variations would be less if a major vent were opened so that most of the gases moved up the well. The temperatures at the top of the stairwell could also be expected to respond more significantly to changes in fire intensity if the fire were nearer the bottom of the well.

Comparison of the outputs of Thermocouples 4 and 5 in Figure 20 with Thermocouples 17 and 18 in Figure 22 shows that the average temperature levels during the entire burn period were quite similar in the vicinity of the room of fire origin in Building 1, Experiment 1 and in Building 2. However, temperatures at the third floor landing also are quite similar

for both fires even though the fire origins are on different floors. The first floor of Building 2 was not significantly heated by the fire while it was confined to the burn room.

2. Building 3

Temperatures in and around the shelter in Building 3 are shown in Figure 23. The burnout of light combustibles (boxes) over the shelter starting at 1:17 p.m. is clearly shown by Thermocouples 3 and 4. The collapse of the first floor ceiling directly over the shelter apparently occurred in stages between 1:50 and 2:00 p.m. The lasting effect of the mixture of heavy combustibles and non-combustibles thus deposited atop the shelter is very evident. Thermocouples 1 and 2 near the shelter ceiling show that the long-duration, low intensity fire in contact with the shelter ceiling causes substantial heating of the shelter. In contrast, the hot gases produced by the fires in the south end of the basement starting at 3:30 p.m. had only minor effects on the temperature of the shelter interior although gas sampling (See Section IV-C) showed significant infiltration by fire gases. Had the fire originated in the first story over the shelter, the resultant debris could be expected to contain non-combustibles and hence enhanced the temperature rise of the shelter space.

C. Gases

The direct monitoring of gas concentrations using a single analyzer has posed numerous problems in past experimentation. For measurements of O_2 concentrations, slow sensor response has limited the frequency with which samples can

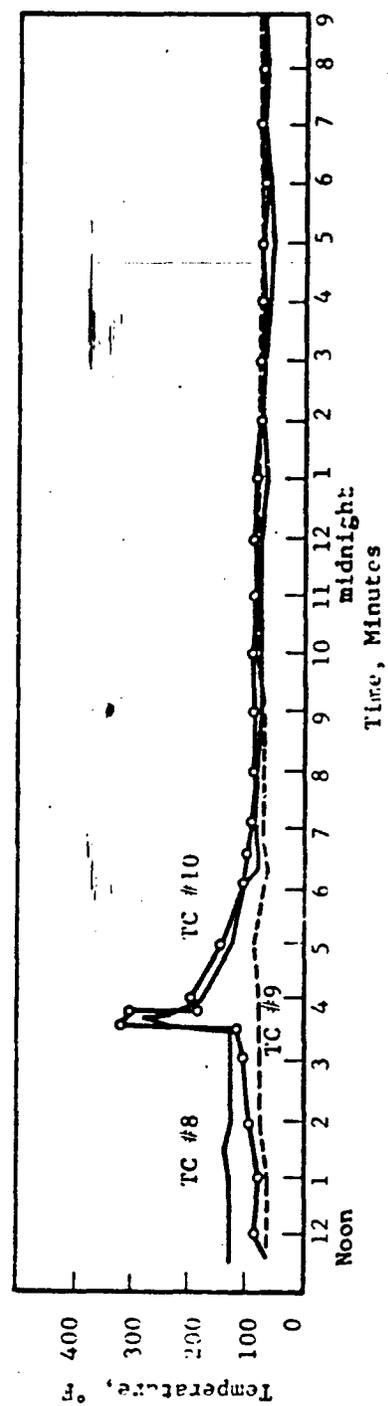
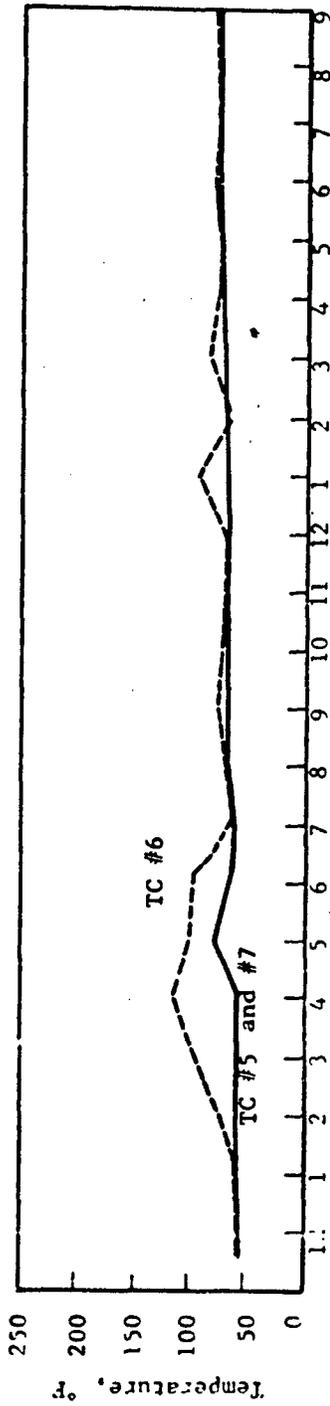
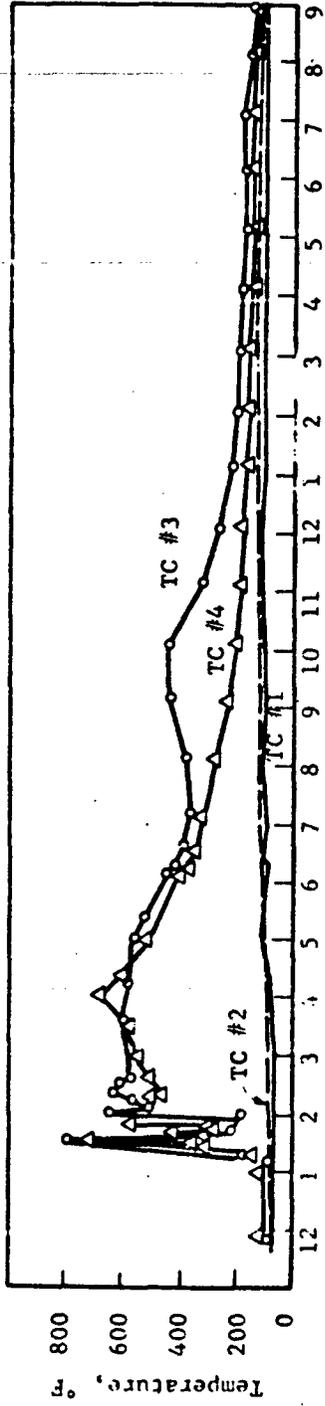


Figure 23. Temperatures, Building No. 3

be taken. This problem existed throughout the present experiment and has only recently been solved by the addition of sensors to the instrument package. Far more serious problems existed with the equipment for CO analysis. This equipment employed catalytic combustion of the CO and required frequent calibration checks during experiments. In addition, it was extremely sensitive to pressure changes and to moisture which collected in the lines during the cooling period between experiments. To overcome these difficulties, an instrument using infra red absorption was used to obtain a limited amount of data in Building 2 through a temporary hookup. For Building 3, it was connected permanently into the automatic sampling system and satisfactory monitoring of all gas sampling lines was achieved.

1. Buildings 1 and 2

Oxygen and CO concentrations measured during Experiment Building 1 are shown in Figure 24. The CO concentrations are those obtained with the catalytic combustion analyzer. Two samples were collected from Line 5, one just before and one just after the peak concentration was reached (near 5 minutes). Mass spectrometer analyses were made of these samples and are reported in Table II. These analyses show that the analysis of total combustibles produced by the catalytic combustion analyzer do give a true measure of CO concentration in this type of fire gas atmosphere.

Analyses from Experiment 2, Building 1 are shown in Figure 25. Data for CO concentration from Line 1 were lost

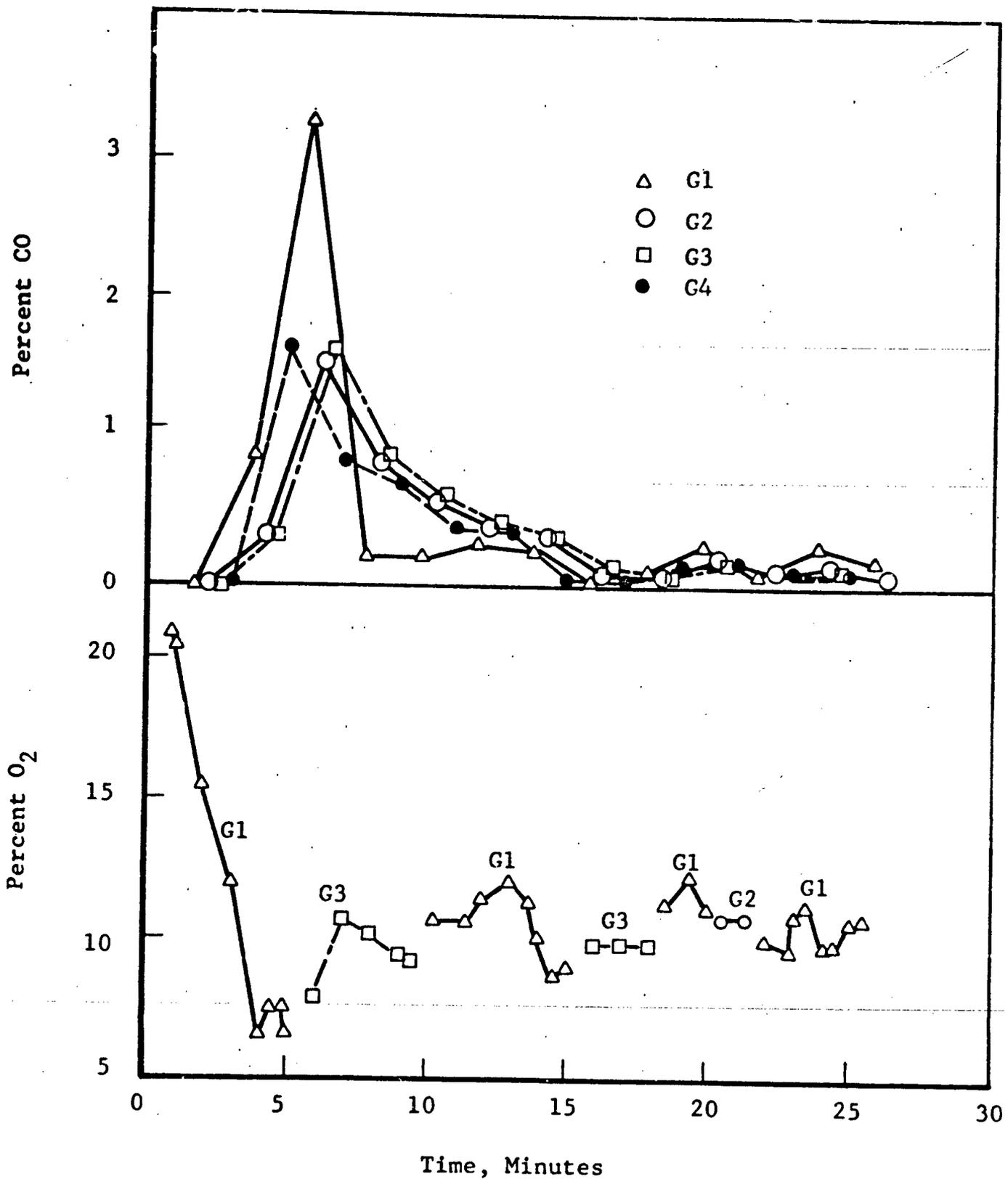


Figure 24. Gas Samples from Experiment 1, Building 1

TABLE II
MASS SPECTROMETER ANALYSES OF GASES
EXPERIMENT 1, BUILDING 1

Component	Composition in Mole Percent	
	<u>Sample 1</u>	<u>Sample 2</u>
Hydrogen	0.04	0.01
Oxygen	8.9	7.5
Nitrogen	77.3	77.5
Carbon Monoxide	1.3	1.0
Carbon Dioxide	11.5	13.1
Argon	0.92	0.89
Methane	0.02	0.01
Ethane and heavier hydrocarbons	0.01	0.01
Oxides of nitrogen	0.01	0.01
	<u>100.0</u>	<u>100.0</u>

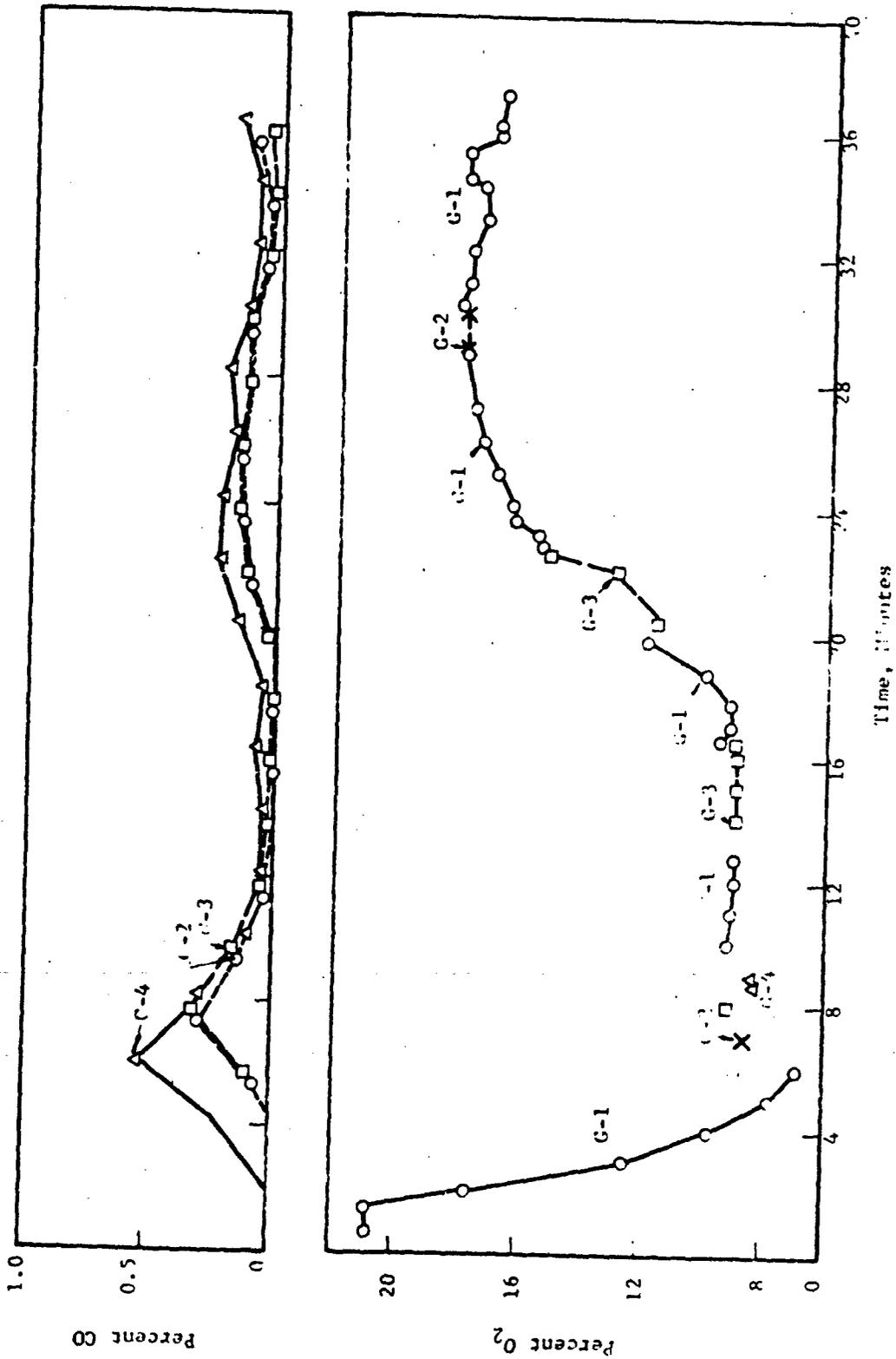


Figure 25. Gas Samples from Experiment 2, Building No. 1

due to moisture collection in the line. The CO data from Lines 2, 3 and 4 were obtained with the total combustibles analyzer.

Shortly after ignition in Building 2, calibration was lost on the combustibles analyzer, apparently due to catalyst poisoning. Whatever the exact reason, results for CO are limited to those obtained with the infra red analyzer which had been temporarily attached to the system. The CO and O₂ concentrations measured in Building 2 are shown in Figure 26.

The absolute magnitudes of the CO concentrations measured in Buildings 1 and 2 have little significance. Many different CO-time relationships can be expected from real contents fires under varied ventilation conditions. As stated earlier, ventilation in these experiments was restricted to assure a measurable amount of CO production.*

What is of interest from these results is the magnitude of CO and O₂ concentrations at each location relative to those existing in the immediate fire zone. The positions of the peak CO concentrations in Figure 24 show clearly the time intervals required for fire gases to move from the burning room to the various gas sampling stations in the building. If allow-

* In retrospect, measurement of the dilution of gases during their movement through the corridor and stairwell might have been more readily assessed by monitoring CO₂ instead of CO. CO₂ was certainly in more constant production throughout each burn and at the temperatures found to exist away from the fire, little reaction should occur to disturb the CO-CO₂ balance.

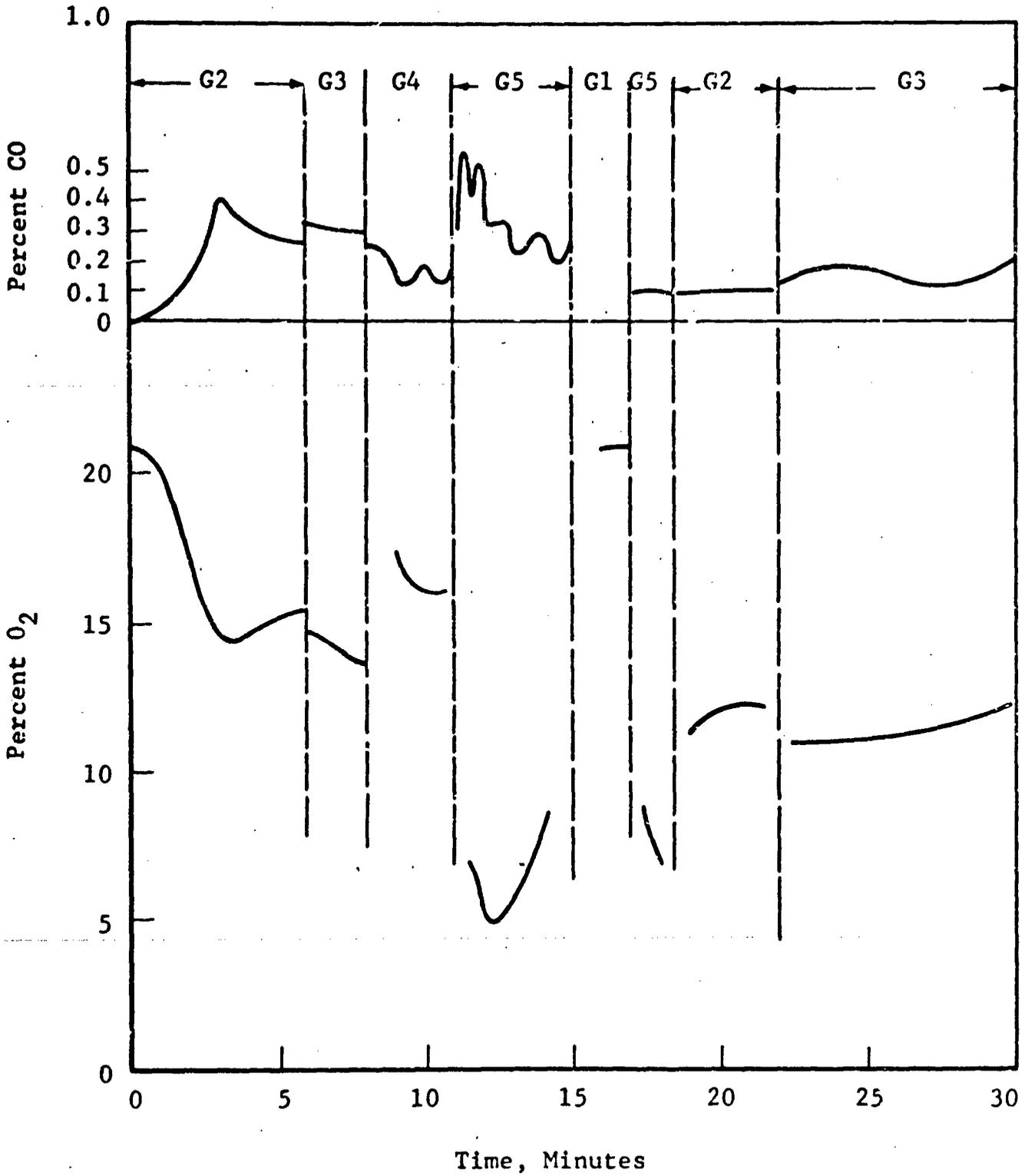


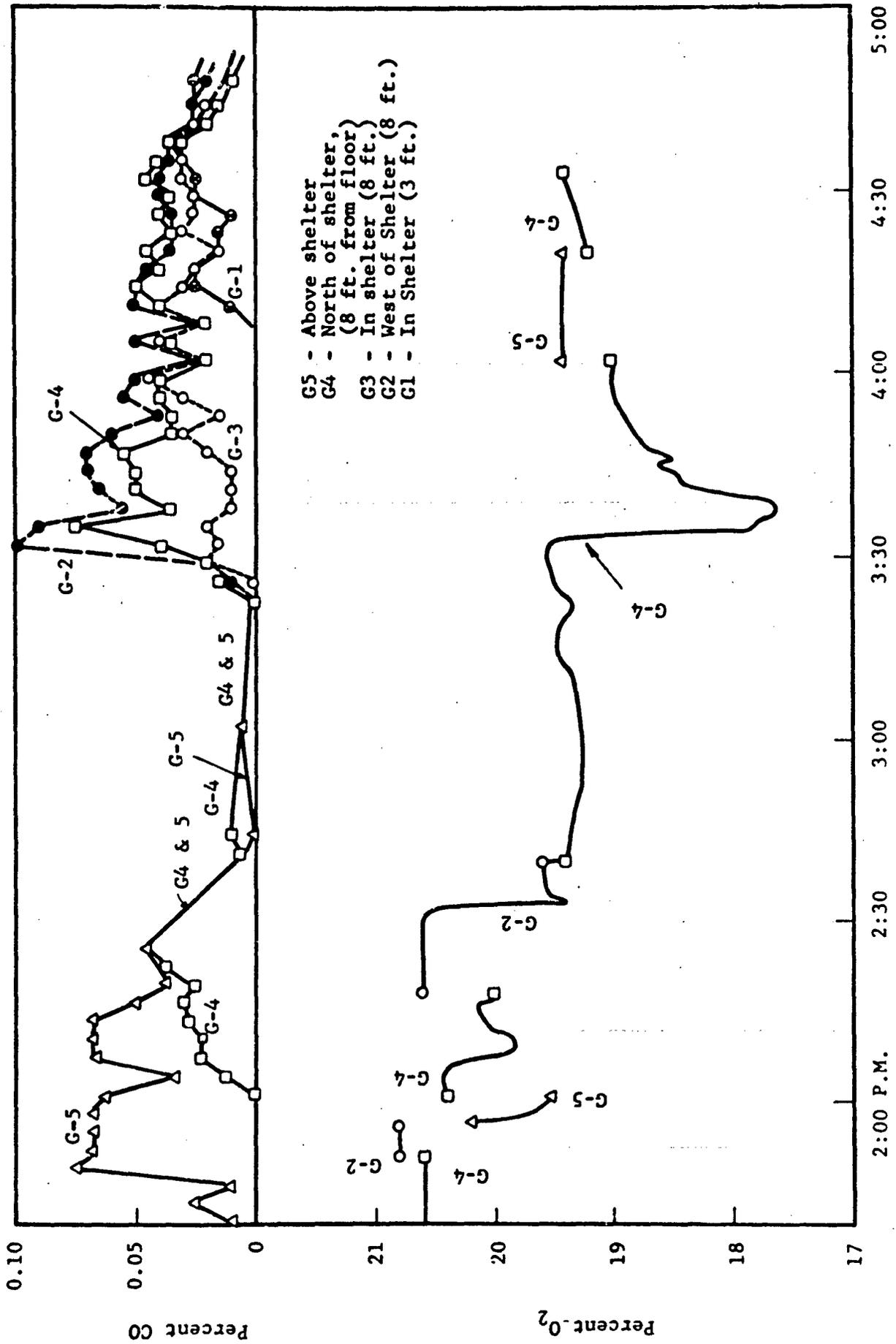
Figure 26. Gas Samples from Building No. 2

ances are made for these time intervals, it appears that very little change occurred in the CO content of any particular quantity of gas as it moved through the corridor and stairwell except close to the fire itself. It may be inferred that the same is true of oxygen content. Although the data on oxygen concentration are not complete, that shown in Figures 24, 25 and 26 tend to substantiate this inference.

2. Building 3

Analyses of gas samples collected in Building 3 are shown in Figure 27. Examination of the results for CO concurrently with those for pressure differences shown in Figure 31 is instructive. During the period of measurable CO generation on the first floor (mainly from 1:40 to 2:40 P.M.) the pressure within the shelter was greater than that on the first floor, thus CO would not have penetrated any minor leaks in the shelter ceiling. During part of this period (2:00 P.M. on) CO was present in the basement north of the shelter (probably generated during penetration of basement door at M) and pressure differences favored gas penetration to the shelter. However, the shelter wall was intact and no CO was detected in the shelter.

Fire at the dumbwaiter (Q) (3:30 - 5:00 P.M.) produced significant CO concentrations west of the shelter (near its door) and pressure differences carried the gases into the shelter space. The shelter door was tightly closed but not



sealed around the perimeter. One can only speculate on the reason for movement of gases out of the shelter to maintain reduced pressure within the shelter. The walls and ceiling appeared to remain intact although sealing of several pipe openings had been made before the burn which may have allowed some leakage to the first floor. Another possibility (more likely) is that suction was somehow created by the pipe which carried pressure taps, sampling lines and thermocouple wires out of the building. (This pipe can be considered quite similar to a shelter vent pipe.) Although sealing of the lines within the pipe had been attempted, the possibility of air flow in this channel was quite good.

D. Pressure

Pressure records are shown in Figures 28 through 31. Those for Buildings 1 and 2 were obtained by time lapse photography of the gauges and visual observation by fire department personnel. The data for Building 3 were recorded directly in the instrumentation trailer as described in Appendix A. A northeast wind impinged directly on the openings to the burn room of Building 1 and caused the pressure in the corridor-stairwell to be higher than that in other parts of the building. The wind was westerly during the burning of Building 2 so that the burn room windows were on the downwind side while the corridor and stairwell were on the upwind side. Leakages through cracks around other openings into the corridor-stairwell were sufficient in this case to

III RESEARCH INSTITUTE

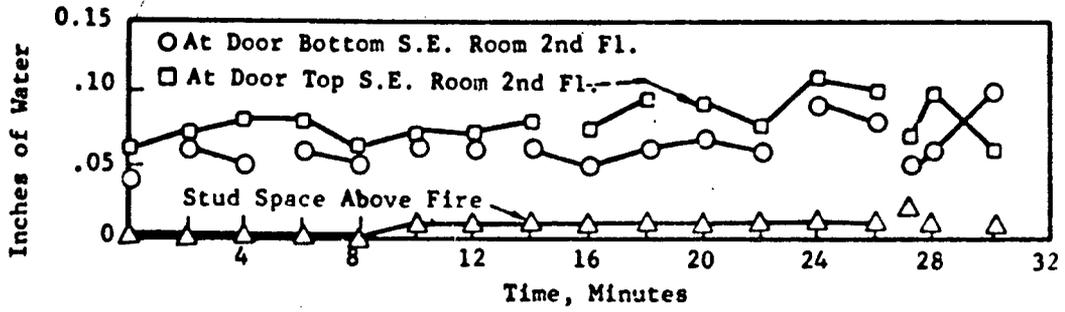


Figure 28. Experiment 1, Building 1

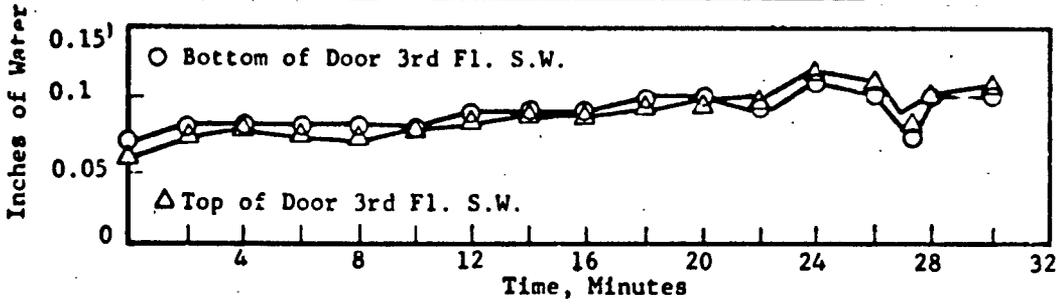


Figure 28. Experiment 1, Building

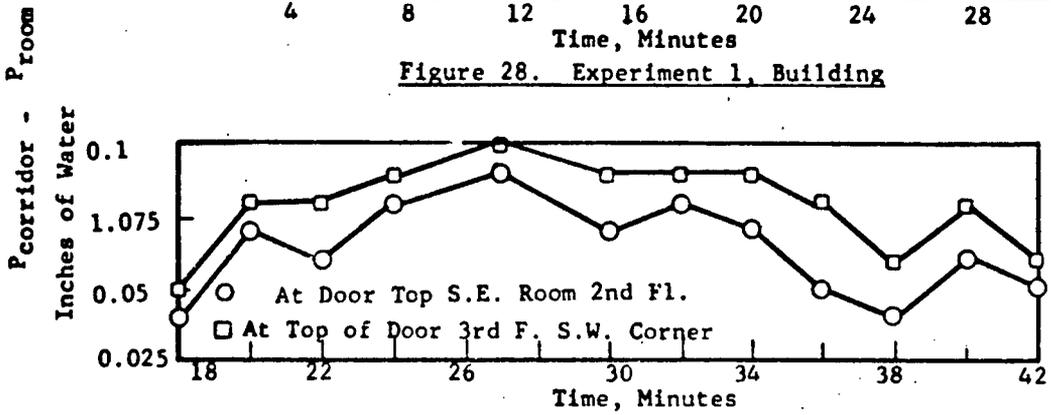


Figure 29. Experiment 2 Building 1

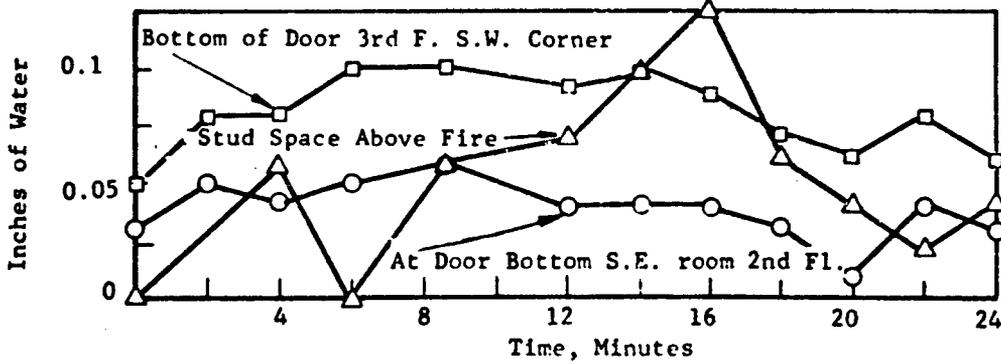


Figure 29. Experiment 2, Building 1

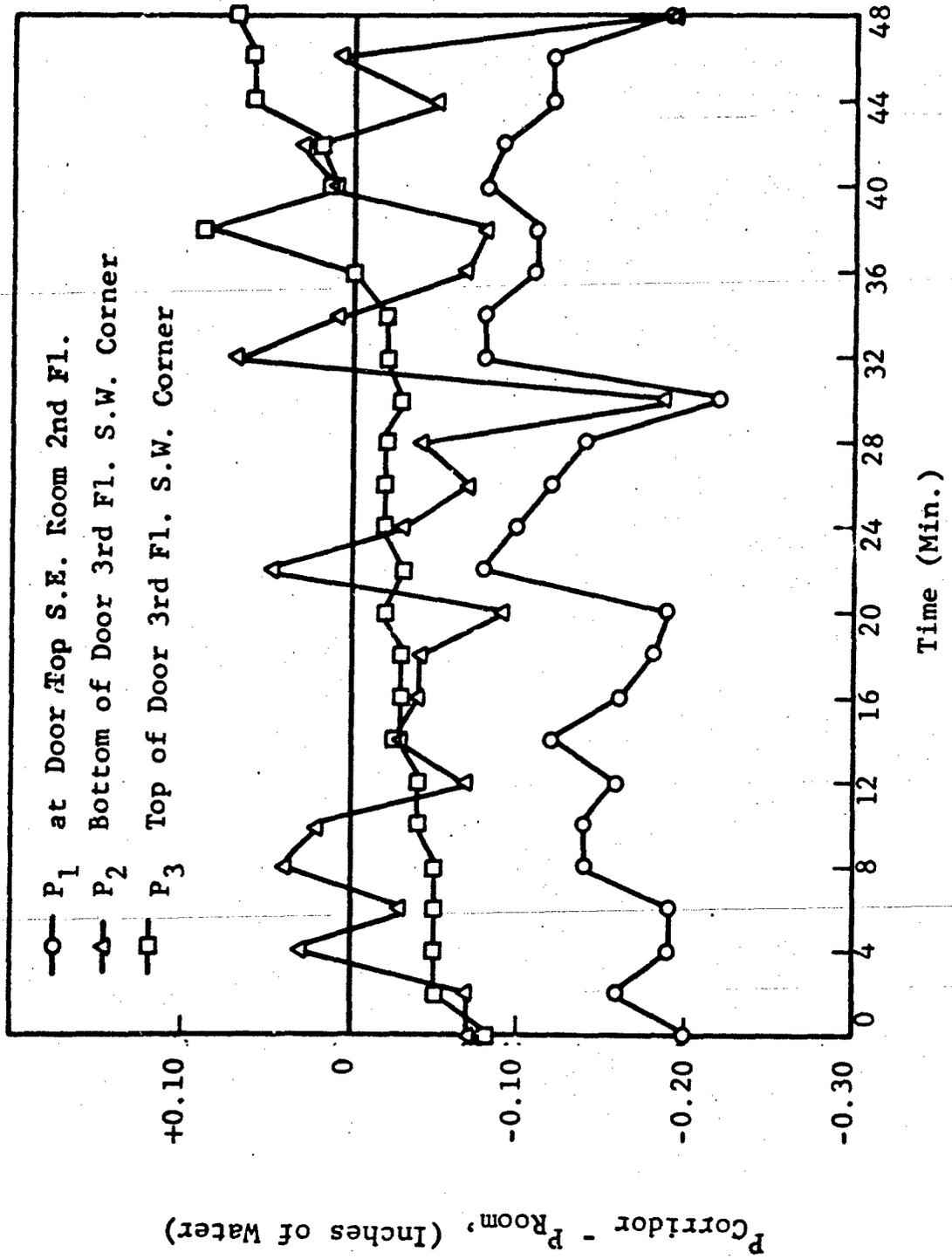


Fig. 30 PRESSURE RECORDS - BUILDING NO. 2

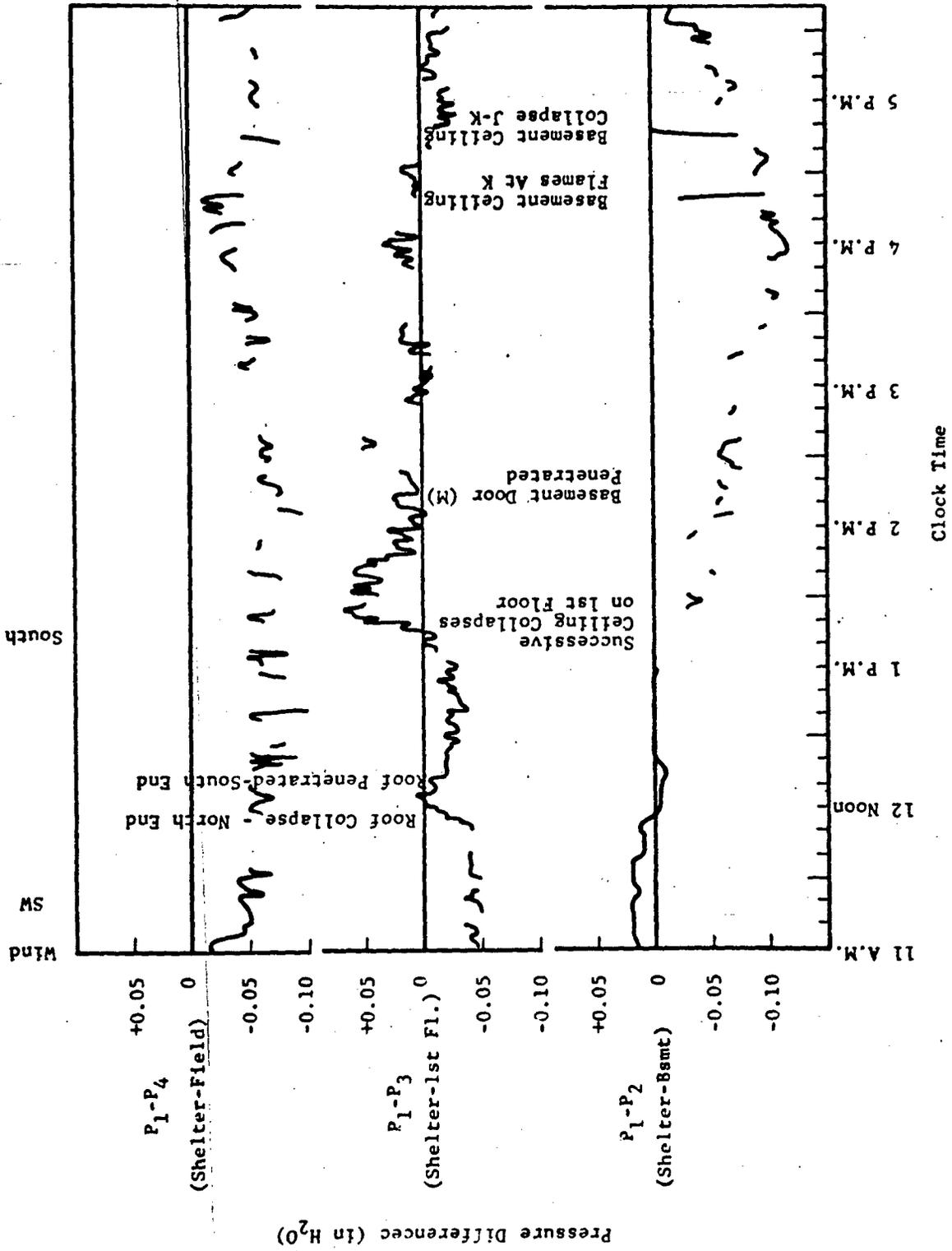


Figure 31. Pressure Differences Recorded During Burn #3 (Waukesha, Wisconsin)

create some pressure excesses in the corridor-stairwell over rooms on the downwind side even. This subject is briefly discussed by Labes⁽²⁾ using air infiltration data from the ASHRAE Guide.⁽⁷⁾

The combined effects of fire and wind on pressure differences are probably most clearly shown by data from Building 3. This structure experienced extreme variations in ventilation conditions and fire locations as the experiment progressed and these changes are reflected quite clearly by the pressures shown in Figure 31. The combined effects of pressure and gas concentration are discussed in Section IV-C.

Pressures measured in the ceiling joist space directly over the fire in Building 1 show a mechanism for spread of gases other than bulk flow of combustion products. A pressure rise apparently caused by heating and generation of wood distillation products in the stud space appeared in both fires. Such pressure buildup in the wall and ceiling spaces of masonry, wood joist structures during fire causes the distillation products to flow out of all possible exits and may result in gas movement and CO buildup in spaces located at levels lower than the active fire zone. High CO concentrations detected well below the active fire zone in a previous fire experiment⁽⁵⁾ probably came about by this mechanism.

E. Firebrands

The subject of firebrand generation was considered early in the planning stages of the burns. At that time, the problem was conceived to be one of finding the ultimate location of the occasional brand leaving the fire. Two schemes were thought to be applicable: 1) covering a portion of the downwind area with a grid of 3 ft. wide paper strips, and 2) visual observation of several specified downwind areas. It was decided to place several observers downwind of the first building and, if brands could be spotted, make arrangements to use the grid approach on subsequent burns at locations selected on the basis of the first fire. Past experiences with several one and two story frame residences and a three story brick apartment building suggested that prolific firebrand production would not occur in these buildings since none had wood shingle roofs and no very tall channels were involved.

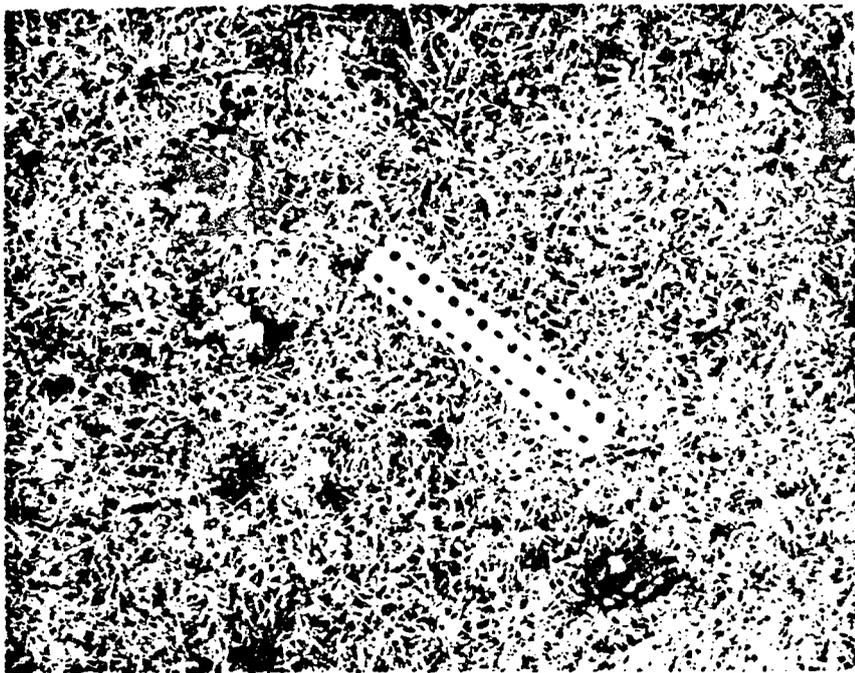
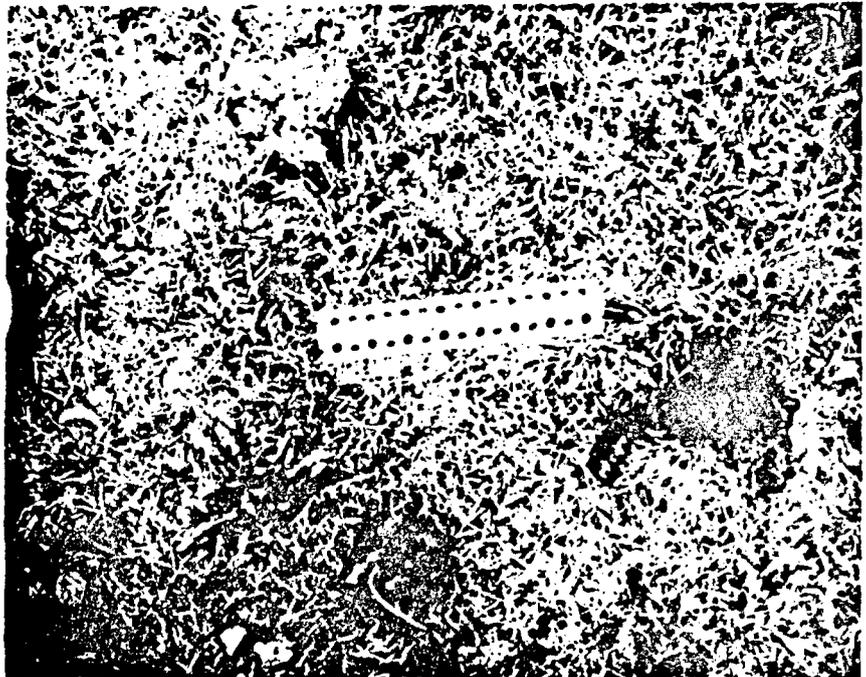
As the roof began to open up on Building No. 1, this notion was quickly proven false. The sky became filled with large numbers of burning embers. Observers stationed one block downwind reported a sound like rain falling on dry leaves as the brands dropped around them. Thoughts of rolling out a small grid were quickly discarded as it was realized that the paper would probably burn as fast as it was unrolled. Several boxes placed behind the instrument trailer one hundred feet

downwind of the nearest corner of the building suffered numerous ignitions. In addition, a rotted tree crotch 1/4 mile from the fire was ignited. Fire patrols reported significant brands well beyond this and hose lines were directed toward the column to help reduce the number of brands leaving the immediate area. As the fire had served its prime purpose and now fully involved the structure, some water was directed into the structure to reduce the fire intensity. Thus, the brand density shown in the accompanying photographs (Figures 32 and 33) would have been even greater under a completely free burn. Completely free burning was not found possible and Building No. 2 was treated in much the same manner as No. 1. For Building No. 3, water application was restricted to the north half of the structure and the convection column. The south half of the structure burned from the top down and was not as violent a fire; thus brand production was quite limited. In the north half, however, fire spread rapidly upward and actively involved the total height. Even with the use of water to reduce fire intensity, brands were found more than a mile from the structure.

Examination of the brands showed most of them to be part of the roof sheathing (nominal 2" x 6" tongue and groove boards). Due to their steep pitch, the roofs had no underlayment and only a single installation of shingles (in spite of the building age). Apparently the lack of thickness and weight of the roof covering permitted the sheathing to remain

III RESEARCH INSTITUTE

150 ft. from fire
(For Reference, the per-
forated angle included in
each picture is 12" long,
holes in each row are on
3/4" centers)

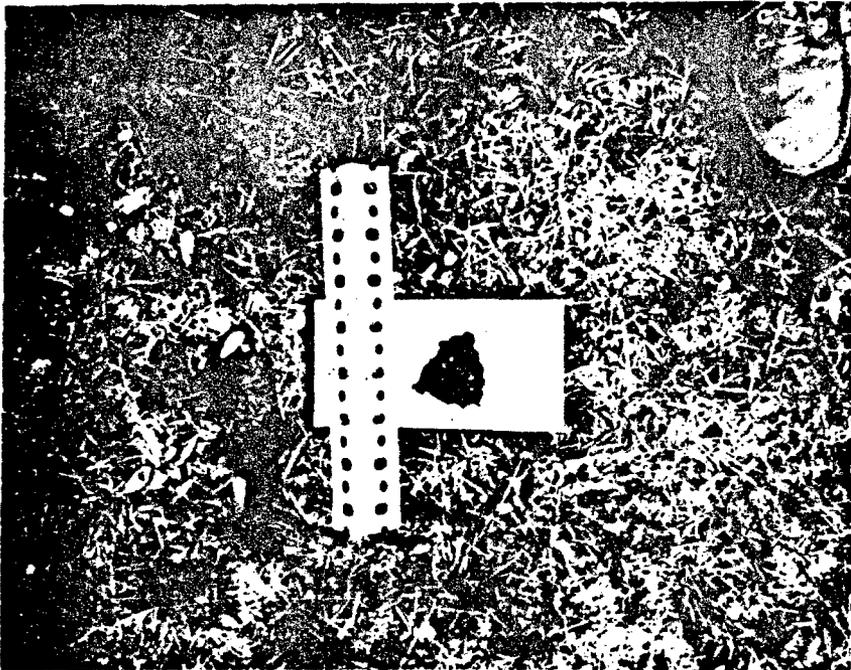
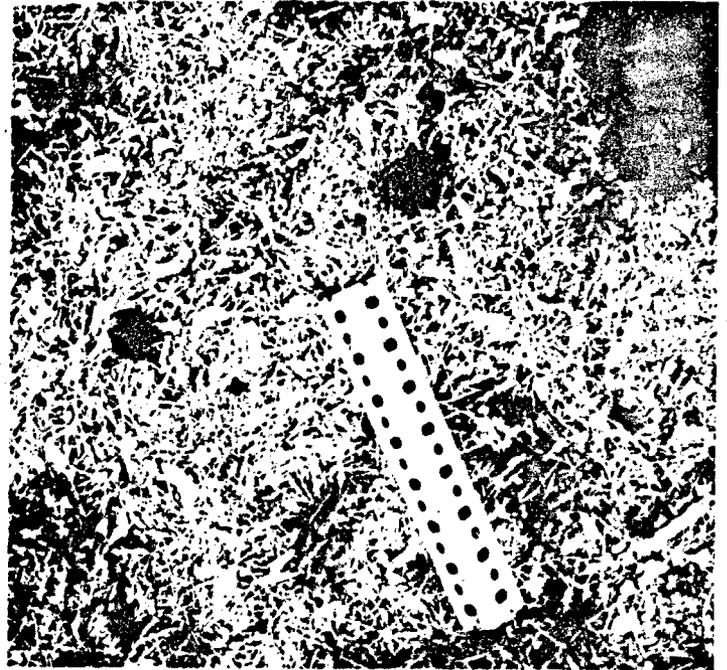


250 ft. from fire

(Note, Indicated firebrand
density is low due to fire
intensity being reduced by
directed water streams)

Figure 32. Examples of Firebrands from Building No. 1

300 ft. from fire



1/4 mile from fire

Figure 33. Firebrands from Building No. 1

in place and readily float away in the updraft of the three story fire.

F. Miscellaneous

1. Ignition of Laundry Building

Two ignitions of the laundry building adjacent to Building 3 occurred during the burnout of Building 3. The first of these occurred at a second floor window on the west end of the north side of the building (see C, Figure 19). The smoking of the window frame had been noted prior to ignition and the ignition was by radiation (possibly piloted by a spark) as no brands were seen flying in the area at the time. Since none of the radiometers were at the exact location oriented perpendicular to the main fire as it existed at this time, the exact radiant heat flux received by the window frames is not known. Radiometers 1 and 2 (on the west side, north end of the laundry) were nearby and offer some indication of flux level (see Fig. 34). At no time, however, did these radiometers indicate levels required for pilot ignition of wood ($0.3 - 0.4 \text{ cal/cm}^2\text{-sec}$). Because the radiometer outputs were not recorded continuously, it is possible that high radiation peaks occurred which were not recorded (such as that at about 11:46, Radiometer 2). Sharp radiation peaks could result from momentary puffs of flame associated with sudden structural changes within the building. As a matter of fact, a series of minor collapses occurred within the north attic at about the time the laundry window ignited, and the roof collapsed shortly afterward. One may speculate

THE RESEARCH INSTITUTE

that after long duration heating of the laundry window at low level, a short period of high radiation produced by the collapse may have been sufficient to produce sustained flow of the window frame. Future full scale experiments might well employ continuous recording of radiation with fast response instruments in order to determine the magnitudes of such radiation peaks. Such information would certainly be of value in determining the ability of fire to spread to adjacent buildings by purely radiative heating.

A second ignition of the laundry building in a door window (H, Figure 19) can probably be attributed to a branch. The subsequent increase in radiant intensities at the window location (see Radiometer 3, Figure 34) supported the burning and resulted in rapid spread up one side of the frame to the top of the window. Since the glass had been removed from the upper corner to accommodate Radiometer 3, the fire spread into the attic space of the laundry. Both laundry fires were extinguished with hand equipment.

2. Conditions after the Fires

Due to their massive construction, only minor wall collapse occurred in Buildings 1 and 2. The same can be said of Building 3 except where the steel work used in the dining hall and auditorium areas weakened the walls (see Figure 35).

Conditions above and around the shelter are shown

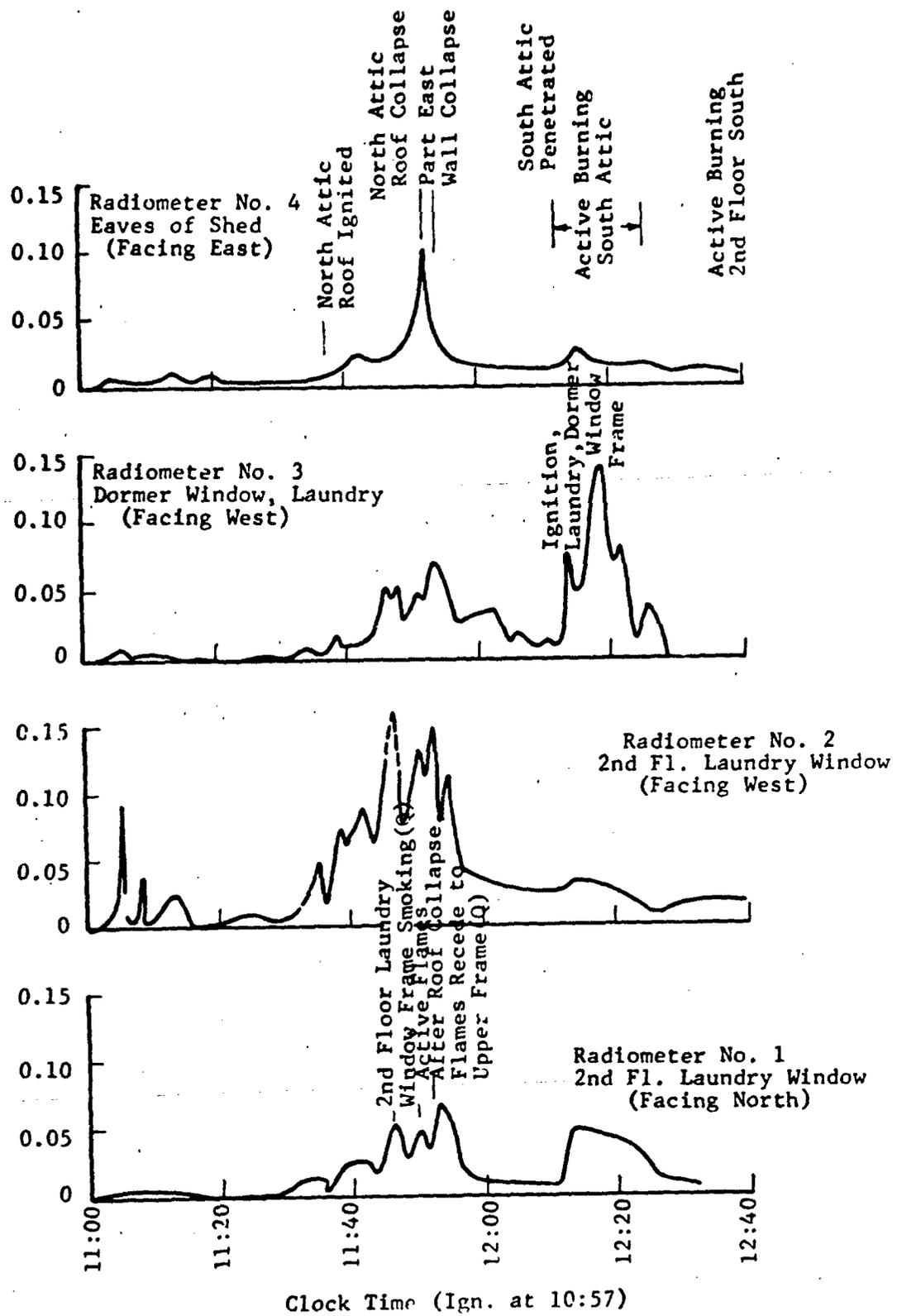
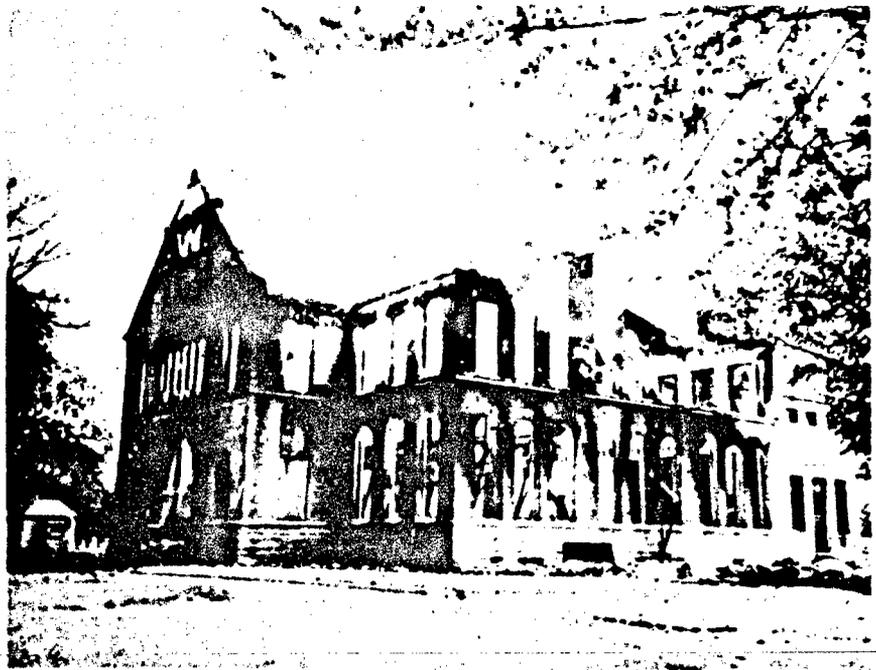
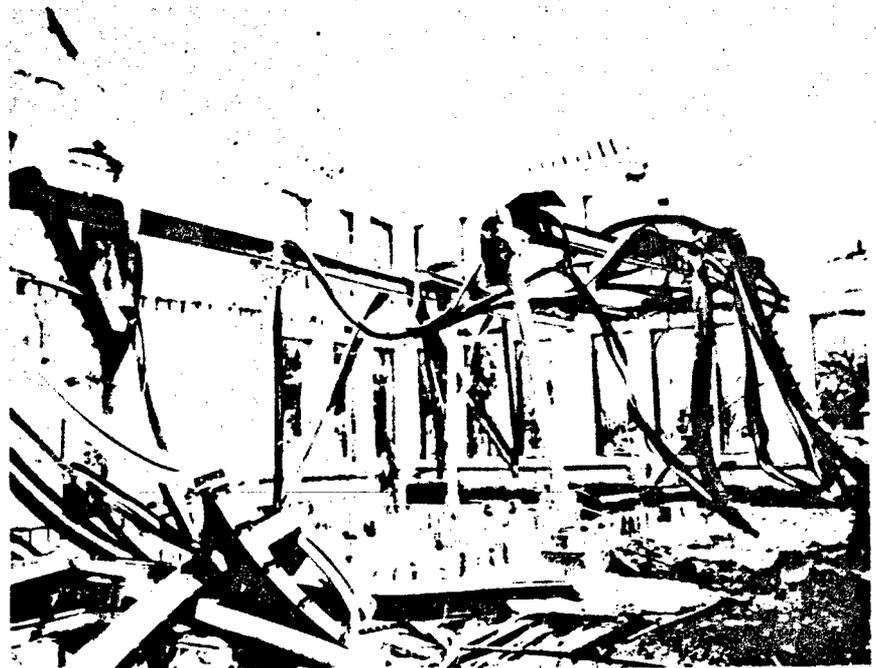


Figure 34. Radiant Flux, Building No. 3 (Waukesha, Wisconsin)



Exterior northwest corner of building



Interior of dining hall

Figure 35. Building No. 3 after the Fire

Figure 36. Because the spread of fire was downward in the south half of Building 3, the amount of combustibles within the debris deposited on the shelter roof by the collapse of the first floor ceiling was probably less than would have been present had the fire originated on the first story.

V. CONCLUSIONS

The conclusions derived from the experiments are listed below. Where applicable, revision of or additions to the interim technical guidance provided in Chapter 7 of Reference 7 are suggested. The conclusions are:

1) Oxygen depletion in an active fire zone will be reproduced throughout interconnecting spaces on the same or higher stories of a relatively "tight" structure or structural portion (unless very large volumes are being considered). In experiments with Buildings 1 and 2, O_2 levels as low as 5% O_2 were measured.

2) CO concentrations of about 75% of those in the active fire zone would have existed at the exterior of shelters removed from the fire but on the same or higher story (addition to interim technical guidance). A maximum of 3.3% CO was recorded in these specific experiments.

3) Wind pressures can drive fire gases into shelter spaces even if fire generated pressures are not significant. Smouldering fires may produce significant infiltration of toxic gases by this means (revision of interim technical guidance is suggested, namely raising pressure potential to

III RESEARCH INSTITUTE



Debris above shelter (chimney
is back wall of shelter)



South and west sides of shelter
(Note: Debris on basement floor
is not due to fire)

Figure 36. Shelter in Building 3 after the Fire

0.5" water for all fire situations including distant flame exposures from individual nearby buildings).

4) Although much more data is needed on real fire environments and movement of fire gases through complex structures, the above conclusions lead to a further statement that fires within a "tight" envelope bounded in part by a shelter cannot be tolerated and must be extinguished unless the barrier between the fire and the shelter is perfectly gas tight.

5) In a fire resistive construction, downward movement of CO will probably not occur.

6) Fire gases infiltrating a shelter having otherwise cool floor, walls and ceiling do not significantly heat the shelter air space and would represent a hazard only because of toxicity or the ignition of combustibles immediately adjacent to their ingress point within the shelter. In Building No. 3, the CO concentration stayed below 0.05% in the shelter; however, not much higher concentrations occurred outside the shelter in this particular fire.

7) The external heating of walls, floor or ceiling in a shelter is a significant hazard and the effects are likely to be long lasting because of the large heat capacity of the shelter envelope. In this respect, the presence of burning combustibles mixed with non-combustibles in direct contact with the shelter produces long-term heating and is particularly dangerous. Ceiling temperatures in the designated shelter area of Building No. 3 reached levels of 130°F (70°F rise) which lasted well

over 2½ hours for a rather moderate debris piling.

8) Due to the cooling effect of walls and ceilings, the temperatures of gases moving horizontally within a structure fall rapidly and should not significantly degrade barriers which are remote from the active fire zone. This is not necessarily true for vertical gas movements such as would occur when the fire and barrier being considered are separated only by a vertical shaft.

9) Provision for complete sealing of shelter vents to outside should be considered to prevent lowering of shelter pressure by suction through the vent. When outside conditions permit the vent could be used to pump air into the shelter thus producing positive flow out through any voids in the shelter envelope.

10) Variations in construction, otherwise considered minor may have a significant effect on firebrand generation. This subject needs further investigation.

11) Local fire and engineering services can collect meaningful data from building burns. They lack only guidance toward a more detailed understanding of the non-extinguishment aspects of fires and the specific interests of shelter safety (see Section

VI. USE OF LOCAL FIRE AND ENGINEERING SERVICES FOR BUILDING BURNS

At the time this program was initiated, IITRI had already participated in five field experiments involving fires in real structures. None of the experiments could have been carried out without the close cooperation and support of the local fire services involved. This cooperation and support was enthusiastic

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given in all cases. That the fire services would actively and capably participate in this program and was thus a foregone conclusion. It remained to establish the amount of information on building fires which might be obtained by fire service personnel without the detailed long-term involvement of research personnel with elaborate instrumentation.

As mentioned in the introductory portion of this report, studies of fire and shelter spaces can be approached in two fashions:

1) Study environments caused by fire in buildings without regard to specific shelter locations, and relate shelter performance to these environments in laboratory evaluations.

2) Study the performance of specified shelter locations when exposed to fires within the building housing them.

The first approach offers the maximum potential use of the data collected but requires more measurements. The second, is, perhaps, more amenable to the use of "packaged" instrumentation. No reason is seen at this time to ignore either approach.

A program incorporating local fire service and engineering experimentation has two major needs. The first need would be the provision of necessary instrumentation. The second would be for a document to inform the services of the technical aspects of fire buildup and spread (which they seldom observe in the normal course of their duties) particularly as shelter areas are affected.

Included in such a document would be:

1. types of information desired and why

III RESEARCH INSTITUTE

2. measurements to produce this information
3. experimental procedures (with emphasis on realism in fire loading)
4. matching of buildings and experiments
5. instrumentation
6. presentation of results

Item 4 could also offer guidelines so that particularly useful structures would be recognized and their availability made known for more elaborate treatment.

Experience has shown that fire service manpower is never in short supply at experimental fires. Thus, instrumentation can be of the indicating, rather than recording type and fire service personnel can be assigned to record time-oriented data. Rather inexpensive instrumentation exists at this time for measurements of temperature, pressure and concentrations of CO, CO₂ and O₂.^{*} Simple modifications of existing equipment could provide si meters for radiation measurement. The clock and the camera are, course, readily available. Since experienced firemen are accusto to moving about freely in burning buildings, equipment carried by fireman would be very mobile and a single instrument could monito several locations in many cases. Examination and characterizatio of the structure by fire service personnel prior to burning shoul be no problem, particularly with the aid of local engineering

^{*}The fire service personnel at the Waukesha burns had prior experience in monitoring CO, O₂ and temperature, recorded pressure data and photographed significant events during the fires.

people (each local fire service is already in close contact with the local building department as well as with other appropriate municipal agencies due to their common interests in general building safety).

Professor Gronbeck, whose analysis of the shelter in Building 3 was presented in Section III-E, has assembled one possible combination of steps toward local handling of fire experiments by the fire services and OCD shelter analysts. It uses the "specified shelter area" approach and is given in its entirety below as an example of the methodology although, as mentioned earlier, limiting the fire service experiments to this type of study is not recommended.

Contributions by the Shelter Analyst

"Shelter analysts, as architects and engineers who are qualified by examination and certified by the Office of Civil Defense, are professionally capable of conducting field work as outlined in these procedures.

"Should the decision be made to use the services of the analyst to conduct research for shelter habitability in the fire environment, instructions should be formalized and distributed through the Architectural and Engineering Services, OCD, with subsequent communications handled between the analyst and personnel of the research organization involved.

Elements of Procedure

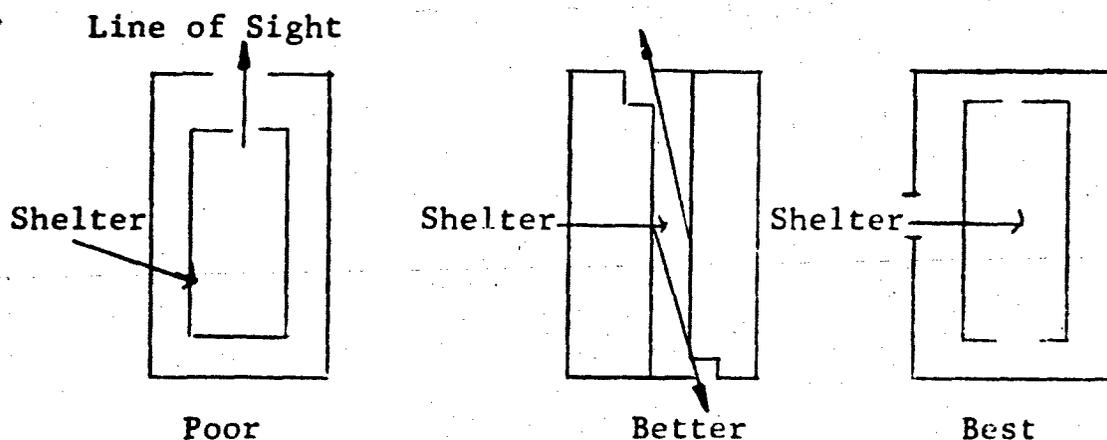
1. "The fire service personnel should have in their possession basic criteria for shelters in order to decide

III RESEARCH INSTITUTE

whether to report shelter potential for a building to be burned. These criteria, or guidelines, should be simply communicated to the fire service in writing and by the use of simple diagrams.

"For example:

- a. Shelter may be on any floor of the building or in the basement of the building
- b. The total thickness of masonry from the inside of the building (shelter) to the outside, should be one foot
- c. The total thickness of the masonry above the shelter should be one foot, measured from ceiling of shelter to roof of building.
- d. There should be no line of sight to the outside from within the shelter. See diagrams below:



2. "If the building meets requirements of the research group, a form should be completed by the fire service and sent to the research group notifying them of the possible test site. The

form should include:

- a. location of building, noting proximity of other buildings
- b. brief description of the building--this may be done by a check sheet
- c. time of burn
- d. reference to Sanborn maps
- e. other information

3. "Upon receiving the notification from the fire service, judgment shall rest with the research group on whether to follow up by participating in the burn. If the research group decides to follow up, a shelter analysis should be made by a qualified analyst. Full instructions should be sent to the analyst. After an inspection of the contemplated test site, the analyst should submit a report to include the following information:

- a. layout and dimensions of building--include any existing drawings or blueprints
- b. indicate type of construction
- c. include photographs
- d. determine a protection factor based on PF estimator
- e. comments and suggestions.

4. "Upon receiving the report of the shelter analyst, a final decision must be made on whether to participate in the burn. If the decision is made in favor of participation, instruments

and equipment should be forwarded with instructions to the analyst. The analyst must work in close cooperation with the chief of the fire services as both will share in the responsibility of a satisfactory burn. Instruments should include:

a. Instruments to record temperature rise in shelter.

A time-lapse photographic arrangement with the camera focused on a wet bulb thermometer, dry bulb thermometer, sensitive barometer, and any smoke, might be used in a "black box" arrangement.

Film should be loaded at the research center with provisions made so that the box need only be set in place and picked up after the burn and returned to the laboratory. Camera box should be insulated against heat.

b. Method of taking samples of shelter atmosphere.

Copper tubing and the use of a vacuum pump of the type accompanying MSA portable Midget Impinger may have application here. Air may be collected in bottles by water evacuation method (some absorption of CO_2 involved). Bottles to be returned to research laboratory for analysis.

c. A vane anemometer should be provided to record wind velocity during the fire. This refers to atmospheric winds and direction.

d. Thermometer should be provided to record ambient outdoor temperature away from fire. A time should

III RESEARCH INSTITUTE

be set for taking wind velocity readings and ambient temperature readings.

"Equipment should include:

- a. Five clip boards with necessary forms. One board to be used by each person taking data; one to each side of the building, and one roving or moving around the burn continuously. The data collected by the person moving around the burn will serve, in a way, as a check on the data collected by the other observers. The form used on the clip board should note time, comments and other pertinent information desired. At the top of the form it would not be amiss to provide examples of the type of comment desired such as, wall collapse, window broken, fire reached roof, etc. The form should ask for the name and the address of the fireman or other person recording data, and a thank you letter forwarded to this person. All watches should be checked at the end of the burn.
- b. Five cameras and film. The camera should be of the instamatic type requiring a minimum of adjustment. Camera might well be loaded prior to shipment to the user. In this way, the user need only aim and shoot. Directions for positioning the camera in relation to the building might also be sent out to the user of the camera to insure that he is not

III RESEARCH INSTITUTE

too close or too far from the building. Color film is preferred, of course. Person recording the data and using the camera might be one and the same. In this fashion a picture might be asked for every five minutes immediately before writing a statement or comment on the progress of the fire. For a comment and a picture every five minutes during the burn for a total time of two and one-half hours of burn time, 30 exposures are required and this will also provide for 150 commentaries on the fire. The extra pictures on a 36 exposure roll of film, which will number six, can be used at the discretion of the user of the camera with the emphasis that only six of the pictures may be taken out of the time sequence. Camera must be returned to the researchers unopened as must all "boxes" used in the burn.

Comment

"The foregoing procedure will supply data on burns of structures having shelter potential and will show habitability of shelters in a fire environment. It must be emphasized to all concerned in the test that the test is being conducted as a scientific undertaking. On this basis, it must be understood that any deviation from explicit instructions must be noted and, if possible, explained by someone recording data

or doing some other task. A team of approximately nine persons, it is estimated, is required for the proper conduct of the test. Each person on the team should have separate printed instructions as to duties and responsibilities."

VII. RECOMMENDATIONS FOR FUTURE WORK

During the preparation, conduct and evaluation of the Waukesha burns, several approaches to the study of fire behavior and its ultimate effect on shelters have been established or revised. These have been forwarded to the Office of Civil Defense in OCD Task Card format at various times during the contract period. It seems proper to reiterate their essential features at this time. These are summarized below along with a description of the studies of OCD Work Unit 1132A to which they, as well as the present task, contribute.

A. Development of Fire Resistance Ratings for Shelter Components (OCD No. 1132A)

1. Approach

The experimental verification of input data for fire test procedures and criteria related to their use in rating shelter components is proposed. These experiments are designed

to:

1. Evaluate temperatures, pressures and gas concentrations representing the many fire situations, specifically
 - a. the influence of fuel surface and ventilation on the exposure characteristics of interior fires
 - b. the exposure due to indirect effects in corridors and vertical shafts which vary in height and leakage rate
 - c. the exposure due to mass fires (laboratory scale experimentation to validate analytical models within this regime) and
 - d. the fuel bed characteristics and atmospheres above debris fires.
2. Evaluate barrier responses to typical exposures, to develop means for predicting these responses from the results of a minimum of standardized tests.
3. Verify the validity of certain peacetime fire test procedures (particularly sample restraint) which are applicable to the rating of shelter components.

B. Other Information

Preliminary studies of the behavior of homogeneous barrier materials under unidirectional heat flow (a part of Item 2 above) are presently being conducted under Contract No. 228 (62479)68580.

C. Background

Present building fire resistance criteria, which are

III RESEARCH INSTITUTE

used for assessing the safety of people within structures under peacetime situations, presume that evacuation will take place and that properly equipped professional fire fighters will soon arrive. Under nuclear attack conditions, however, the shelter occupants cannot reasonably flee the shelter area or building and outside fire fighting cannot be expected. Thus, fires within the shelter area must be controlled by the occupants and fires external to the shelter area must be withstood in their entirety by the structural barriers comprising the shelter envelope. In the case of the fallout shelter, the non-shelter portions of the structure must also be capable of withstanding unsuppressed burnout without endangering the shelter occupants. The additional requirements imposed by the nuclear attack situation are reflected in a need for shelter component fire resistance compatible with these requirements. This study was initiated as one of the tasks under Contract No. OCD-PS-64-50*.

B. Design of Tests for Urban Building Burns

1. Approach

It is proposed to develop a design manual for experimental building fires. The purpose of the manual will be to provide guidance for obtaining information regarding the environment of mass fires and their effects on shelter areas. Particular emphasis will be placed on fires to be conducted in connection

*For further detail, the reader is referred to Labes et al. (Ref. 2)

III RESEARCH INSTITUTE

with OPERATION FLAMBEAU. Subjects to be treated include:

1. types of information desired
2. measurement to produce this information
3. instrumentation
4. experimental procedures
5. presentation of results.

Regarding the types of information desired, these will be subdivided into two categories. One will pertain to the fire environment, the other to the effects on shelter areas. The latter will be correlated with OCD work 1133B, "Design of Tests for Effects of Mass Fires on Shelter Occupants".

An additional subject to be considered will deal with guidance for the preliminary experiments of OPERATION FLAMBEAU.

C. Preparation of "Shelter Habitability in a Fire Environment-
A Design Manual for Fire Service Experiments"

1. Approach

To increase the availability of useable information on fire conditions at the perimeter of shelters, it is proposed to develop a guide for the Fire Services to inform and aid them in the collection of data in a form amenable to this purpose. The proposed document would concern both general fire buildup and spread with specific emphasis on these as they might affect an included shelter area. Subjects to be treated include:

1. types of information desired
2. measurements to produce this information

III RESEARCH INSTITUTE

3. experimental procedures
4. matching of buildings and experiments
5. instrumentation
6. presentation of results.

Item 4 would also offer guidelines so that particularly applicable structures would be recognized and their availability made known so that in these cases more sophisticated and elaborate instrumentation could be brought into operation by research organizations such as IITRI where warranted.

2. Future Plans

The follow-up program would be to release a limited number of the guides to selected fire service groups and to analyze their resulting operations on several experimental burns. The revisions and extensions to the guide suggested by this assessment would then be made and the revised guide given general distribution.

D. Study of Firebrands

1. Background

Quantitative assessments of fire spread for urban areas are presently limited to considerations of radiative contributions. Only the crudest estimates, based on very limited statistics, can be made of the contributions of firebrands or convective heat transfer. Without the inclusion of adequate representations of these modes of spread, all estimates of fire damage and rate of spread (and its associated casualty estimates) will tend

to underestimate damage.

2. Approach

The study of firebrands requires the application of a large number of scientific disciplines to the various stages of a firebrand history. Rather than include all of these here, the present writing attempts only to delineate the major events in the life of a firebrand and to propose solutions to several of the problems concerned with estimating the associated fire hazard. Many of the other necessary inputs to full description of its behavior are presently being studied or exist as proposed tasks on file (ex. the convection column of a fire storm).

The life of a firebrand can be generally subdivided into three intervals of interest, namely: generation, transport and ignition of combustibles. Studies of each of these intervals can generally be conducted independently with no particular requirement of sequential order. Thus, although they will be discussed chronologically, chronological order of study is not implied.

I. Firebrand Generation

The number and size of firebrands produced by a given structural fire is unknown. Wood shingles are identified as serious producers of brands, but beyond this, no quantitative and very little qualitative information is available. It thus seems appropriate to establish the capability of various construction types to produce brands, both as individual fires under low velocity winds and under high winds or in mass fires. An experimental program is proposed which incorporates full scale segments of various roof and floor-ceiling construction in a fire environment and collects all generated firebrands. The experimental lab at IITRI (Gary labs) seems particularly adaptable to this purpose as the present roof (about 18 ft.

III RESEARCH INSTITUTE

above the floor) is flat and has an 8 ft x 8 ft opening which could act as the top of an 8 ft square structure placed below. The remaining roof space could support a simple screen trap to collect the brands. In this manner, the number and size distribution of brands for various construction types could be established. Equipment is available for artificial wind generation.

II. Firebrand Transport

A typical firebrand leaves its point of origin, rises within a convection column, leaves the column at some point and settles to earth. Its final location and size upon reaching this location depend on the relative magnitude of the horizontal and vertical forces which have acted upon it and the resultant time elapsed. Naturally, one must know the nature of the convective column which carries it aloft. Such studies are presently underway or proposed elsewhere. Studies concerning settling velocity and size with time are being conducted by Tarifa et al. in Madrid and it is assumed that their study will eventually include shapes in addition to the cylindrical and spherical ones recently reported at the 10th Symposium (International) on Combustion. Thus, the additional information required for complete description of the trajectory of any specific firebrand is its path while in the convective column. It is proposed to treat the problem analytically by first considering a vertical column where the brand has a mean upward motion due to the column and a fluctuation, both horizontally and vertically, due to the column turbulence. The results of the study will describe the "fallout" of brands at various elevations. A similar treatment of a non-vertical column will be needed but bests awaits development of an analytical model of the conflagration. It is anticipated that it may be sufficient to add a steady, mean horizontal motion to the firestorm analysis for this purpose. Certainly such an approach is a reasonable interim technique.

III. Ability of Firebrands to Ignite Host Materials

To properly evaluate the effect of firebrands, one must establish their ability to cause a significant fire once they land. This ability is a function of the material they contact and, in certain cases, the radiant "boost" they receive from the parent fire. Fire spread by brands into areas where blast has removed windows will certainly be more successful than into areas where windows are intact, due to the obvious susceptibility of interior combustibles to small brands. No program is proposed in this area at this time. Some information presently exists concerning susceptibility of roofing materials (British Fire Research reports).

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APPENDIX A
INSTRUMENTATION

The development of instrumentation for fire experiments is, in itself, an area requiring continuing research. Many of the quantities to be measured are quite small requiring rather delicate sensors and these must function satisfactorily in or near the high temperature environment of the fire. In addition, it is highly desirable to use the same instrument both in the laboratory and in the field. For this reason, a degree of ruggedness is required. Where practical, the sensor can be expended (such as a thermocouple) but the costs associated with construction and calibration of most of the sensors prohibit this as a general practice. Needless to say, many of the instruments are not commercially available or, at best, require extensive modification of commercially available components.

The instruments described herein have evolved over a period of several years of fire experimentation. Their designs permit continuous remote recording of the monitored quantities by measuring D.C. voltages.

1. Radiation

The instrument used to measure radiant flux is of the radiometer or asymptotic calorimeter type. It consists of a thin (0.002") gold disk, blackened on the side facing the radiant source and highly polished on the back. As shown in

III RESEARCH INSTITUTE

Figure A-1, the disk is placed in front of a copper block which serves both as a reference temperature and heat sink. The disk is supported by chromel and alumel thermocouple wires which are connected in opposition to a second thermocouple embedded in the copper block. This differential couple is used as a measure of the radiant flux falling in the disk, convection being blocked by a thin mica window placed over the opening in the housing. To minimize heat pickup, the interior copper block and front housing cover are gold plated and polished. The remaining housing parts are chrome plated.

The instruments were calibrated for radiant flux levels up to $0.04 \text{ cal/cm}^2\text{sec}$ by comparison with the reading from an Epply thermopile, using a device similar to an optical bench for alignment and a bank of eight quartz lamps with reflectors as a source. A shield with a 2 in. x 2 in. opening was placed in front of the lamps to reduce the source size to within the field of view of both instruments. Changes in shield temperature over long time periods will still affect each instrument differently due to their dissimilar viewing angles. To account for this effect, calibration was accomplished by exposing both instruments to the shielded source with and without a shutter across the shield opening as shown below.

Note: Assembly screws omitted for clarity

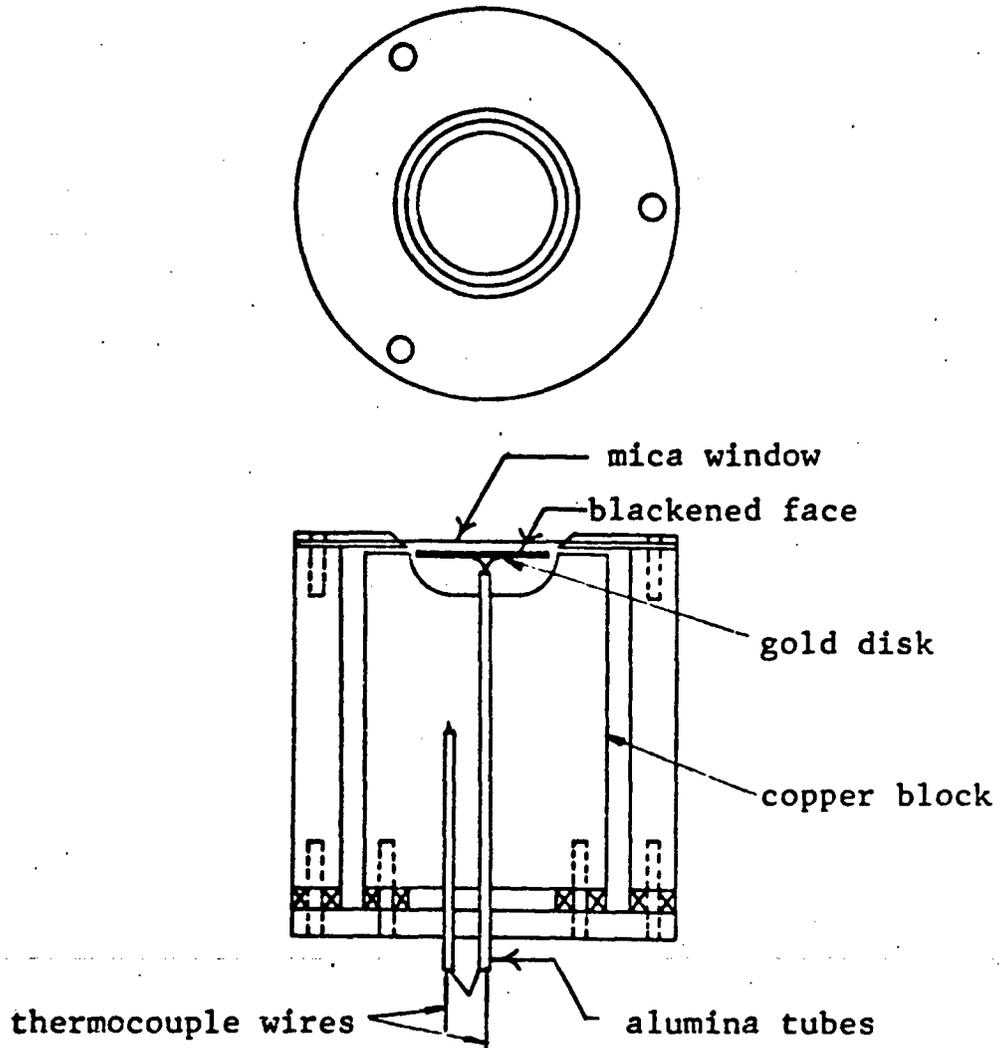
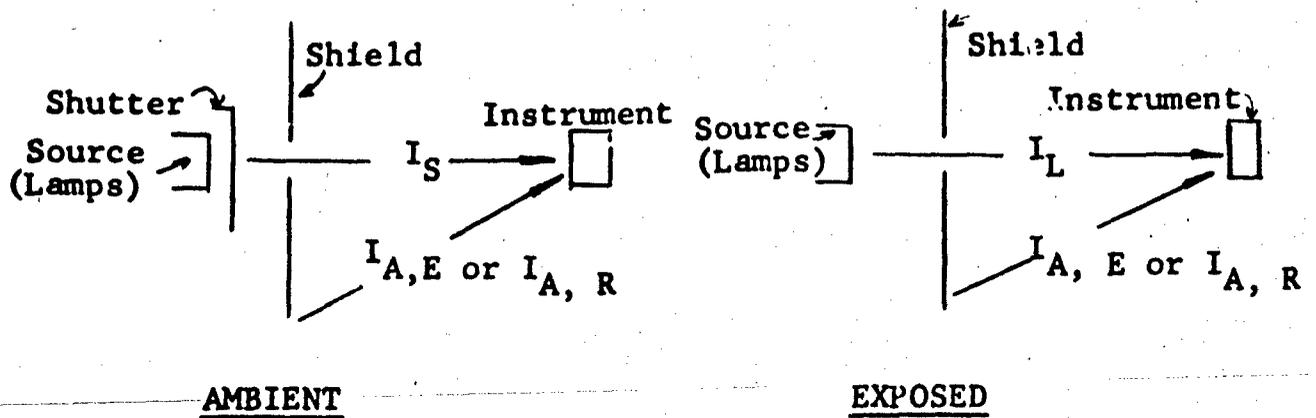


Figure A-1. Radiometer for Measuring Heat Flux from Fires



With the shutter in place, fluxes measured are:

$$I_E = I_{A,E} + I_S$$

and

$$I_R = I_{A,R} + I_S$$

With the shutter open:

$$I_E^* = I_{A,E} + I_L$$

$$I_R^* = I_{A,R} + I_L$$

The subscripts R, E, A, L and S refer to the radiometer, Epply cell, ambient, lamps and shutter respectively. As noted above, $I_{A,E} \neq I_{A,R}$ due to the variation in the angle of vision of each instrument. By subtraction

$$I_E^* - I_E = I_L - I_S = I_R^* - I_R$$

which relates the flux differences measured by each instrument.

For higher flux intensities, beyond the range of the Epply thermopile, the shield was removed and a ten-to-one chopper was placed in front of the radiometer, readings being taken with and without the chopper in use. Comparison of the

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readings, corrected for the radiation from the heated chopper, permitted the use of the radiometer as its own calibration standard for the high range. A typical calibration curve is shown in Figure A-2. A comparison of various radiometers with the curve for a perfectly black receiver absorbing and emitting energy on one side only is shown in Figure A3.

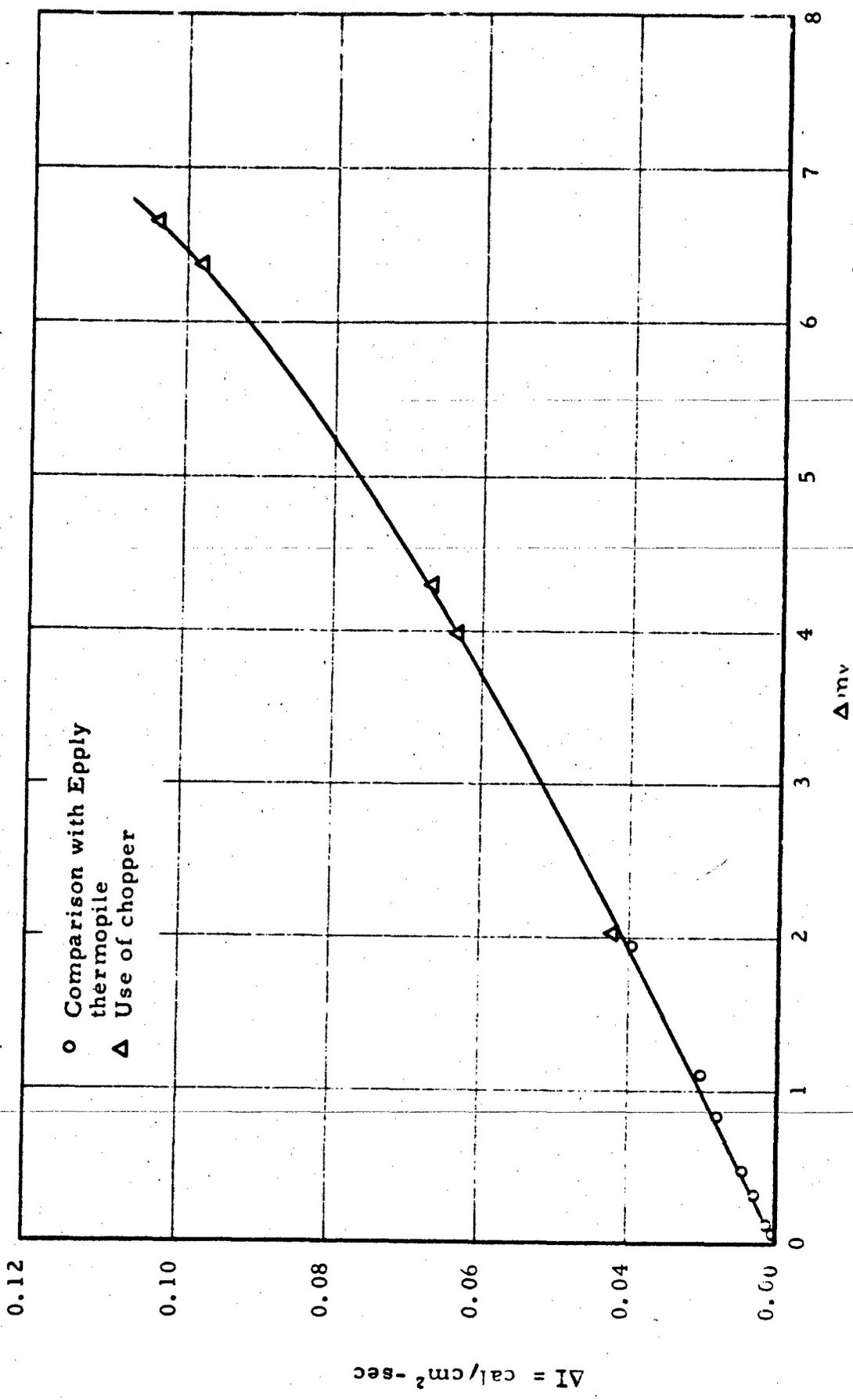
An approximate analysis of the instrument may be obtained by considering only radiant heat transfer from the exposed disk: Consider a flux, I_i , of which ϵI_i is absorbed. If the sink temperature, T_R , is the same as the reference disk temperature and T is the temperature of the exposed disk, then $\sigma F(T^4 - T_R^4)$ is the net radiant interchange between the back side of the exposed disk and the sink. F is defined as

$$F \approx \frac{1}{\frac{1}{\epsilon_{\text{disk}}} + \frac{1 - \epsilon_{\text{Sink}}}{\epsilon_{\text{Sink}}} \frac{A_{\text{disk}}}{A_{\text{Sink}}}}$$

considering the geometric angle factor from the disk to the sink as one. The terms ϵ and A are the emissivity and area respectively. A heat balance for the disk yields:

$$I_i = \sigma T^4 + \frac{\sigma F}{\epsilon} (T^4 - T_R^4)$$

It is noticed that when $T \rightarrow T_R$, $I_i \rightarrow \sigma T_R^4$, the reference flux associated with a zero millivolt reading. Calculations of $I_i = \sigma T_R^4$ check the experimental calibration curve if $F/\epsilon \approx 3$,



$\Delta I = \text{cal/cm}^2\text{-sec}$

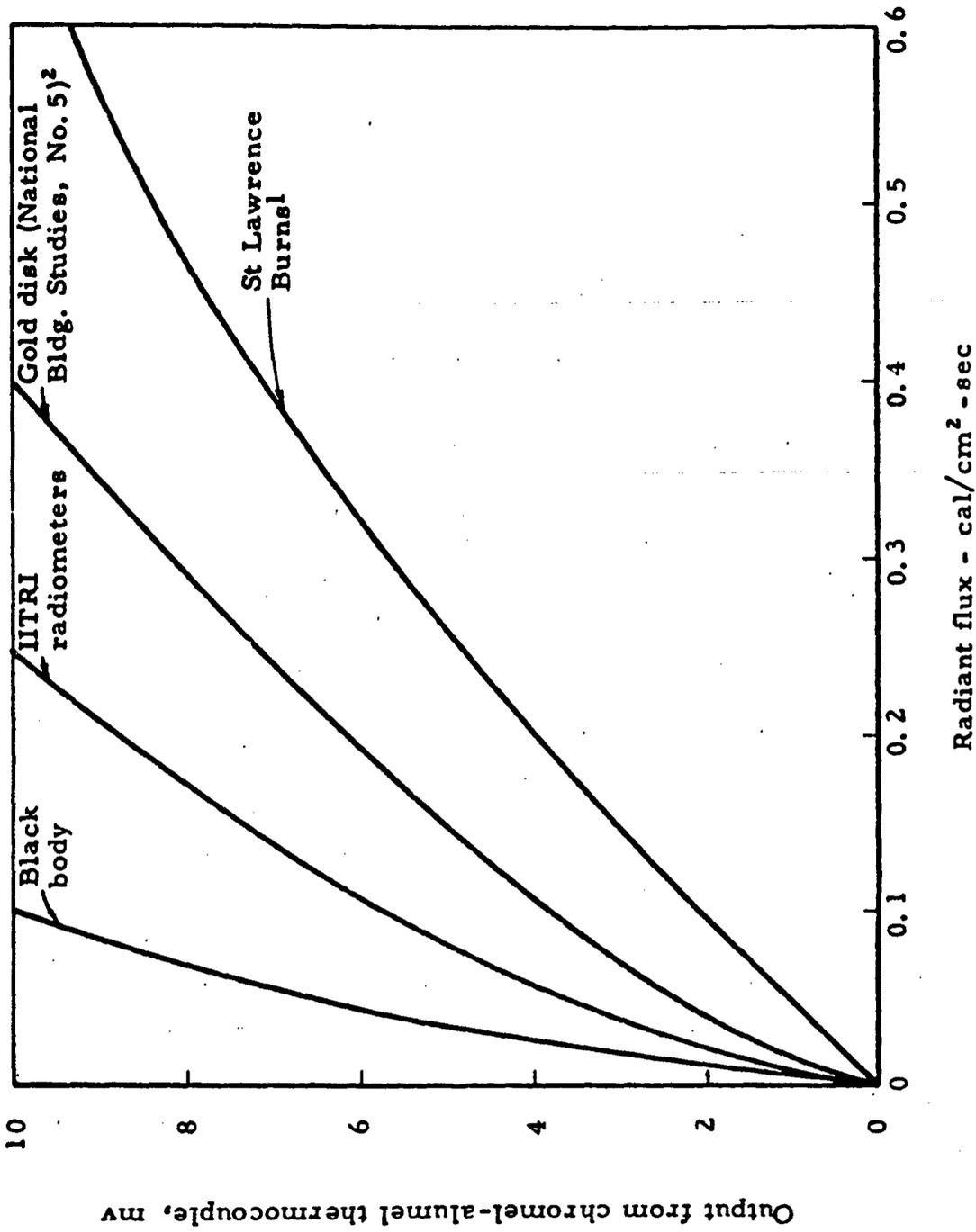


Figure A-3. Comparison of Radiation Measuring Device

up to flux levels of $0.08 \text{ cal/cm}^2 \text{ sec}$. Above this point, the calculated values are higher than the calibration values, indicating possible cooling of the disk due to internal convection.

When the radiometer is used to measure the radiation from a fire, the flux associated with the reading represents the net radiation increase from the fire above that of the background. The total radiation from the fire would be obtained by correcting for that portion of the background blocked by the fire and no longer visible to the radiometer. Fortunately, this correction amounts to less than 0.5 per cent for typical background temperatures (70°F) and may be neglected.

2. Air Velocity

The hot-wire anemometer is commonly used for measuring low air speeds and its sensing element normally consists of a very fine exposed wire which is heated by an electric current. The temperature of this wire and consequently its electric resistance depends on the rate of cooling caused by air flowing over it, and, therefore, it can be calibrated for measuring air speed. A modified instrument is described by Simms⁽⁸⁾ who used a twin-bore silica tube with a resistance-heated element in one hole and a temperature measuring thermocouple in the other. At a sacrifice in response time he was able to achieve greater accuracy and a more stable calibration. Such an instrument, however, cannot be used in

III RESEARCH INSTITUTE

the vicinity of a fire because varying thermal radiation from the flame may overshadow the convective heat transfer due to air flow.

This difficulty has been overcome⁽⁹⁾ by the use of two identical tubes with thermocouples connected in opposition so that the emf signal is a function of the temperature difference between them. If only one tube is slightly heated electrically, the output of the differential thermocouple should depend only on the heating current and on the rate of cooling due to the air flow. The effect of radiant heating from a high temperature source, such as flames, is essentially the same for both tubes and the difference of the heat balances from each tube yields the relation:

$$T - T_R = \frac{I^2 R}{hA} - \frac{\sigma \epsilon}{h} (T^4 - T_R^4)$$

where T and T_R are the temperatures of the hot and reference tubes, respectively, I is the constant current through the hot tube, R the heating wire resistance, ϵ the emissivity and h the convection coefficient. When there is no radiation, the relation reduces to

$$T - T_R = I^2 R / hA$$

In the calibration region, $T - T_R$ is almost directly proportional to the output of the differential thermocouple. The instrument is based on changes of h with velocity in the forced convection region. For small temperature differences:

$$T^4 - T_R^4 \approx (T - T_R)4T_m^3, \text{ where } T_R < T_m < T$$

Then

$$T - T_R \approx \frac{I^2 R / hA}{1 + \frac{\sigma \epsilon}{h} 4T_m^3}$$

indicating that radiation will not affect the calibration if $\frac{\sigma \epsilon}{h} 4T_m^3$ is much smaller than one. For room temperatures, $4\sigma T_m^3$ is on the order of 1 Btu/hr-ft²-°R, $\epsilon/h = 0.01$, and the error due to radiation is only one per cent.

Differential hot-tube anemometers based on the above design were constructed for the fire experiments and are illustrated in Figure A-4. The tubes of each unit were 0.042 i O.D. stainless steel, and the externally-connected differential thermocouple was made of 36 gage (0.005 in. dia.) chromel-alumel wires. One of the tubes contained an insulated 30-gage (0.010 in. dia.) constantan wire as a heating element, the supports serving as electric current leads. Heating of the resistance wire was recorded by monitoring the voltage drop. These hot-tube anemometers are of simpler construction than those described in Reference 10 and offer certain advantages. The use of a single hole metallic tube, instead of twin bore ceramic, assures uniform temperature around the circumference of the tube and thermocouples welded to the tube wall yield a more rapid response time. Gold plating and polishing the tubes reduces their emissivity with a

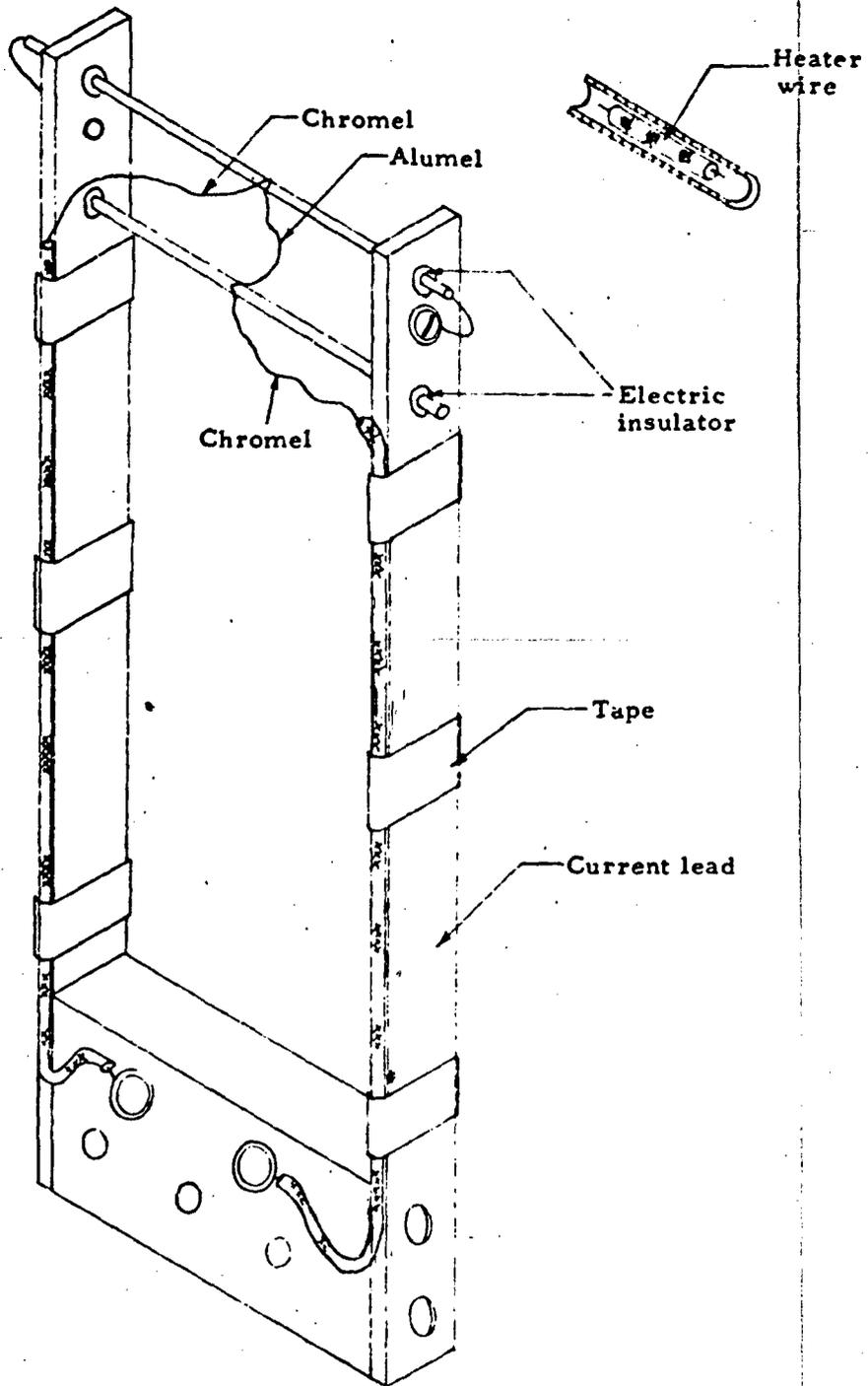
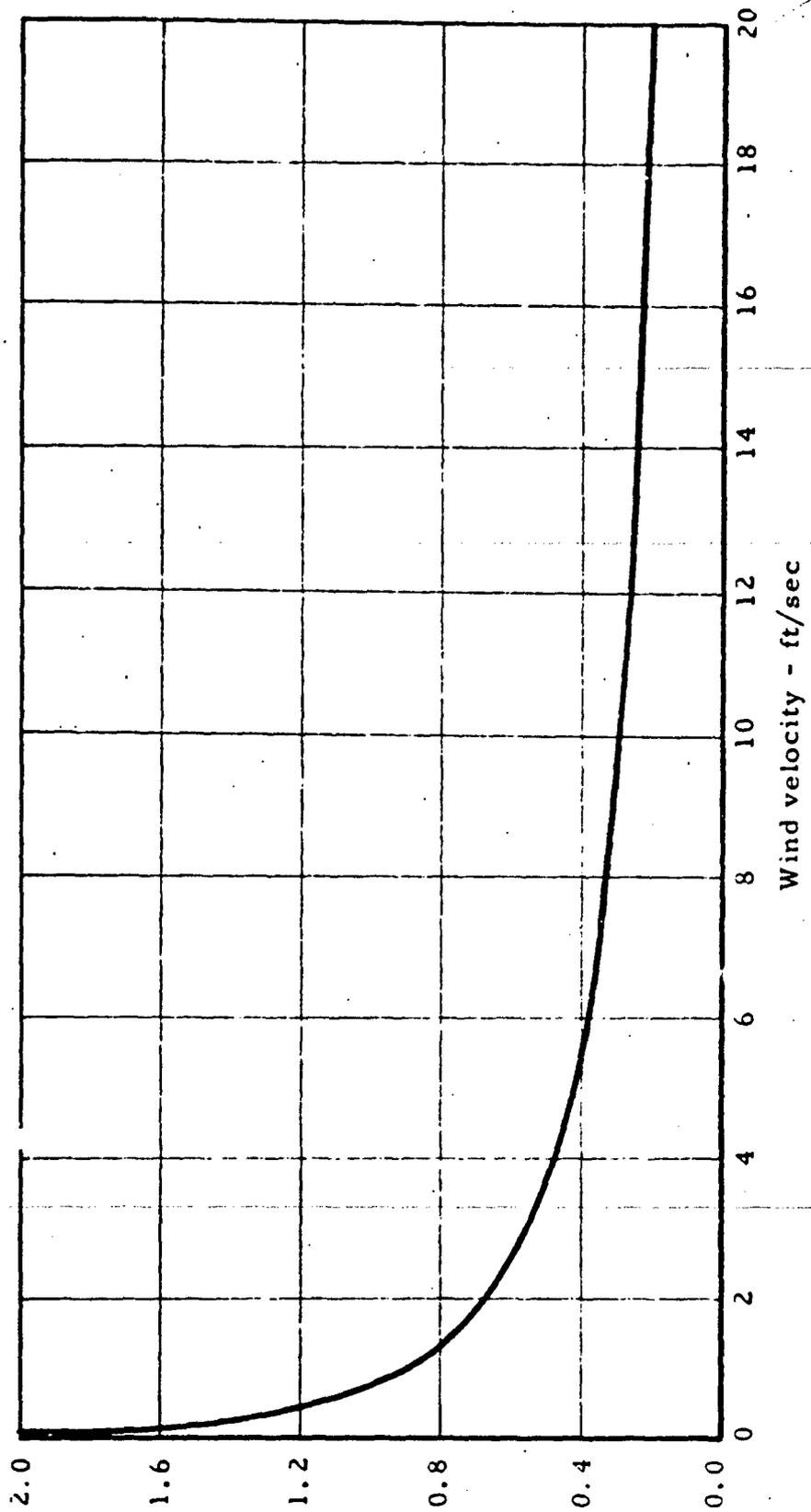


Figure A-4. Hot Tube Anemometer

subsequent reduction in error due to radiation from the fire

Calibration of the anemometers was accomplished by rotating them in an enclosure. Power and thermocouple leads were brought to a series of annular mercury pools where the signals could be picked up by wipers, rotating with the anemometers. This rotation was accomplished by use of a constant speed motor with an adjustable drive. Wind velocity is determined by the rotational speed. A typical calibration curve is shown in Figure A-5.

As one might suspect, the calibration curve is quite sensitive to input current to the heated tube. A 100 per cent error was indicated in the wind velocity from a 15 per cent change of heater current. For this reason, the input current must be carefully monitored and controlled. To accomplish this and to minimize the number of controls required, panels were constructed which operated 1 to 10 anemometers per panel. The anemometers were connected in series through the panel and thus each received exactly the same current flow. A schematic diagram of a panel is shown in Figure A-6. Power was adjusted by means of a variable transformer and the approximate current level measured with a microammeter. To establish a precise, reproducible setting, a resistor was placed in series with the anemometers and, through a rectifier bridge, a D.C. millivoltage monitored. The conversion to a D.C. signal permitted the monitoring voltage to be read on the same recorder



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Figure A-5. Typical Anemometer Calibration Curve

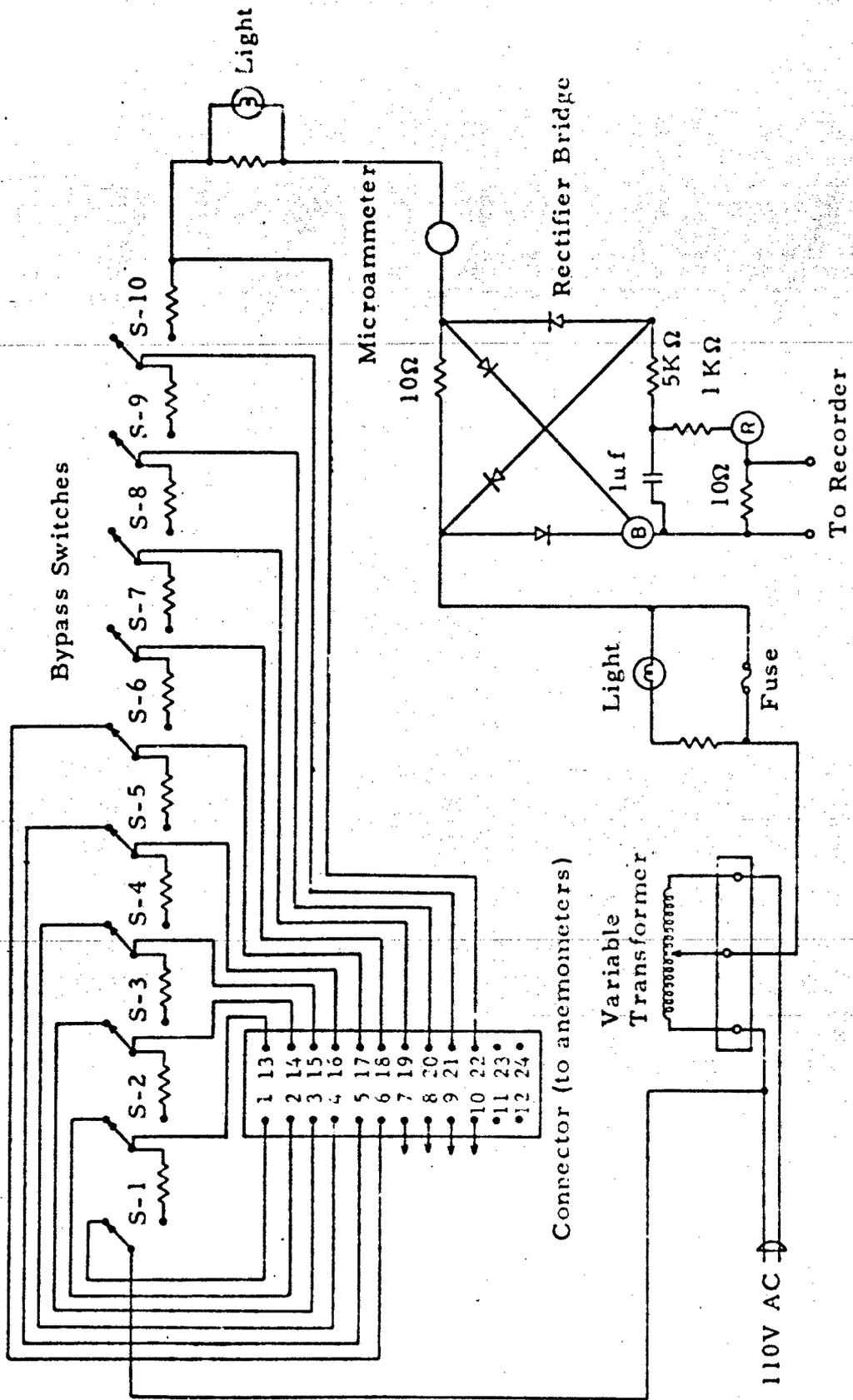


Figure A-6. Anemometer Control Panel

that read the differential thermocouple output of the anemometer.

3. Burning Rates

Burning rates were assessed by measuring weight loss of the cribs placed in Buildings 1 and 2. For this purpose a direct weighing device was used. It consisted of a commercially available unit similar to a household bathroom scale which was modified to permit remote recording by replacing the dial by a low torque potentiometer. Figure A-7 shows the photographs of one of the scales with cover removed. Application of a load to the knife edges through the cover plate causes movement of the slide plate (see top photograph) which in turn rotates the axis of the potentiometer. The rotation of the axis changes the measured portion of the voltage impressed on the potentiometer by the circuit arrangement shown in Figure A-8. The design of the circuit allows connection of 10 scales in series using bypass switches (S-1 to S-10 in Figure A-8). The current flow from a storage battery is adjusted by a potentiometer (R-1 in Figure A-8) and measured by a microammeter (A-1 in Figure A-8) having a range of 0 to 50 μ a. In use, both the total impressed voltage to each scale as well as the portion spanned by the slide contact of the potentiometer were measured. Overheating of any individual scale was thus noted immediately as a variation in total voltage drop through its potentiometer. The result of a typical calibration is shown in Figure A-9.

For the burns in Buildings 1 and 2, the fuel load was

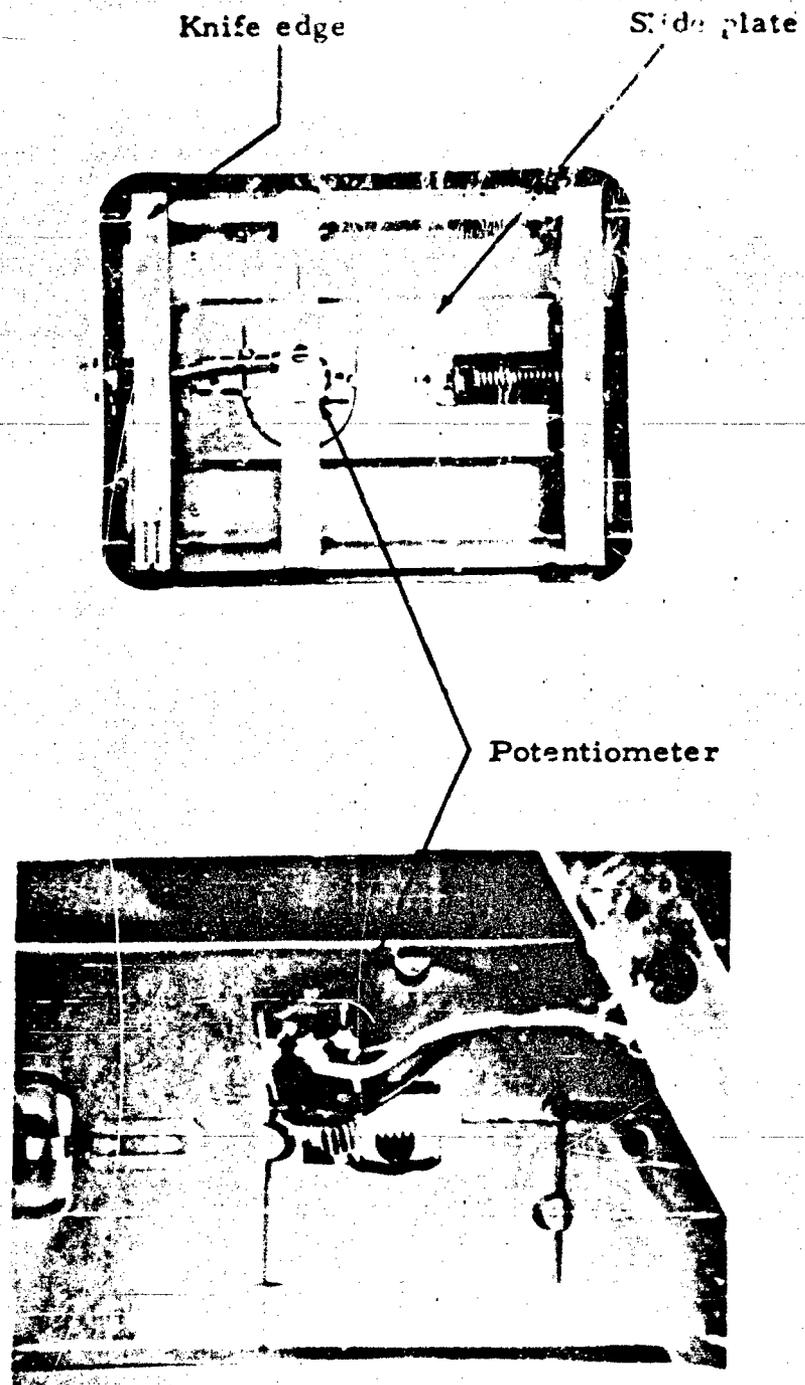


Figure A-7. Photographs of Scales for Measuring Burning Rates

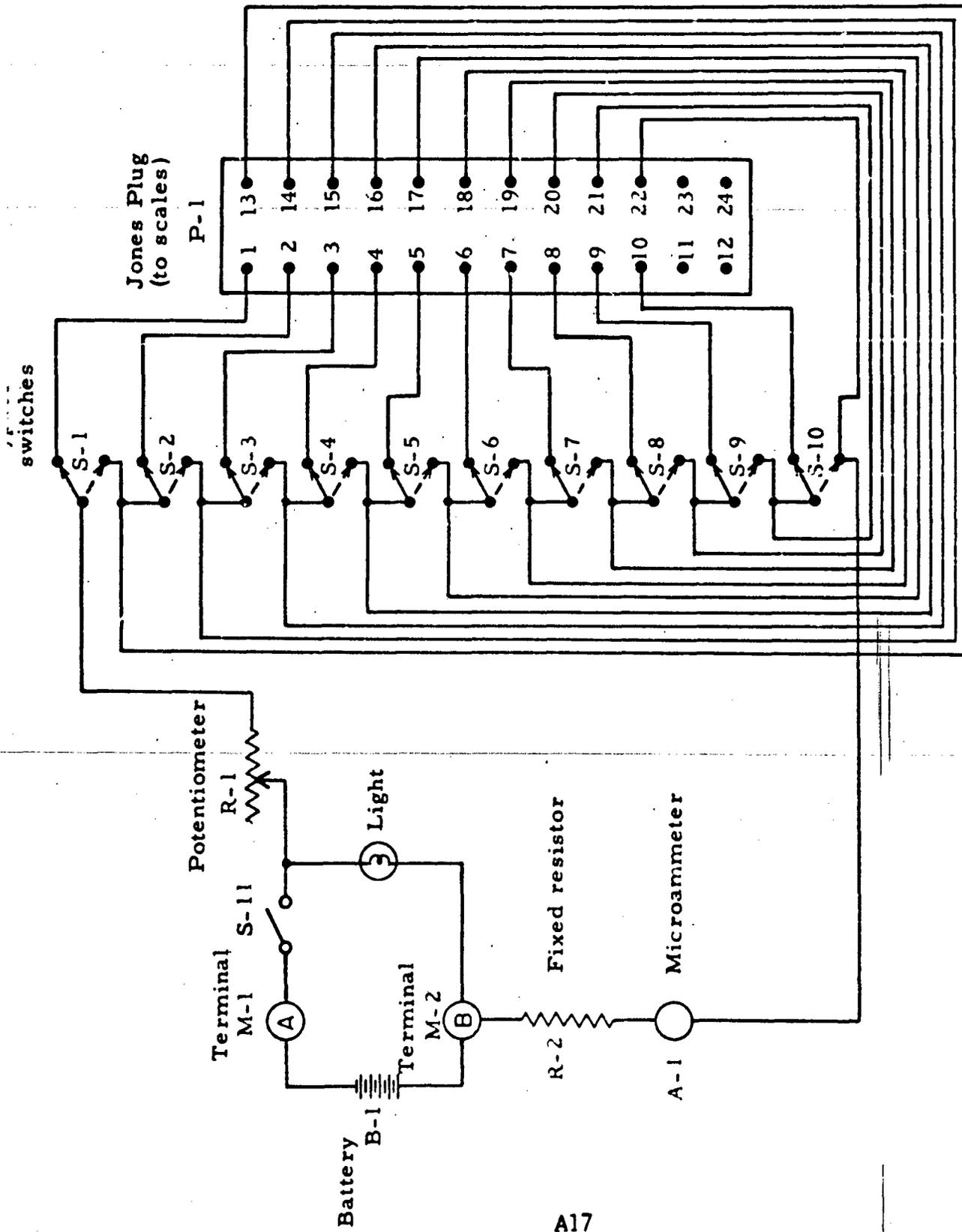


Figure A-8. Scale Control System

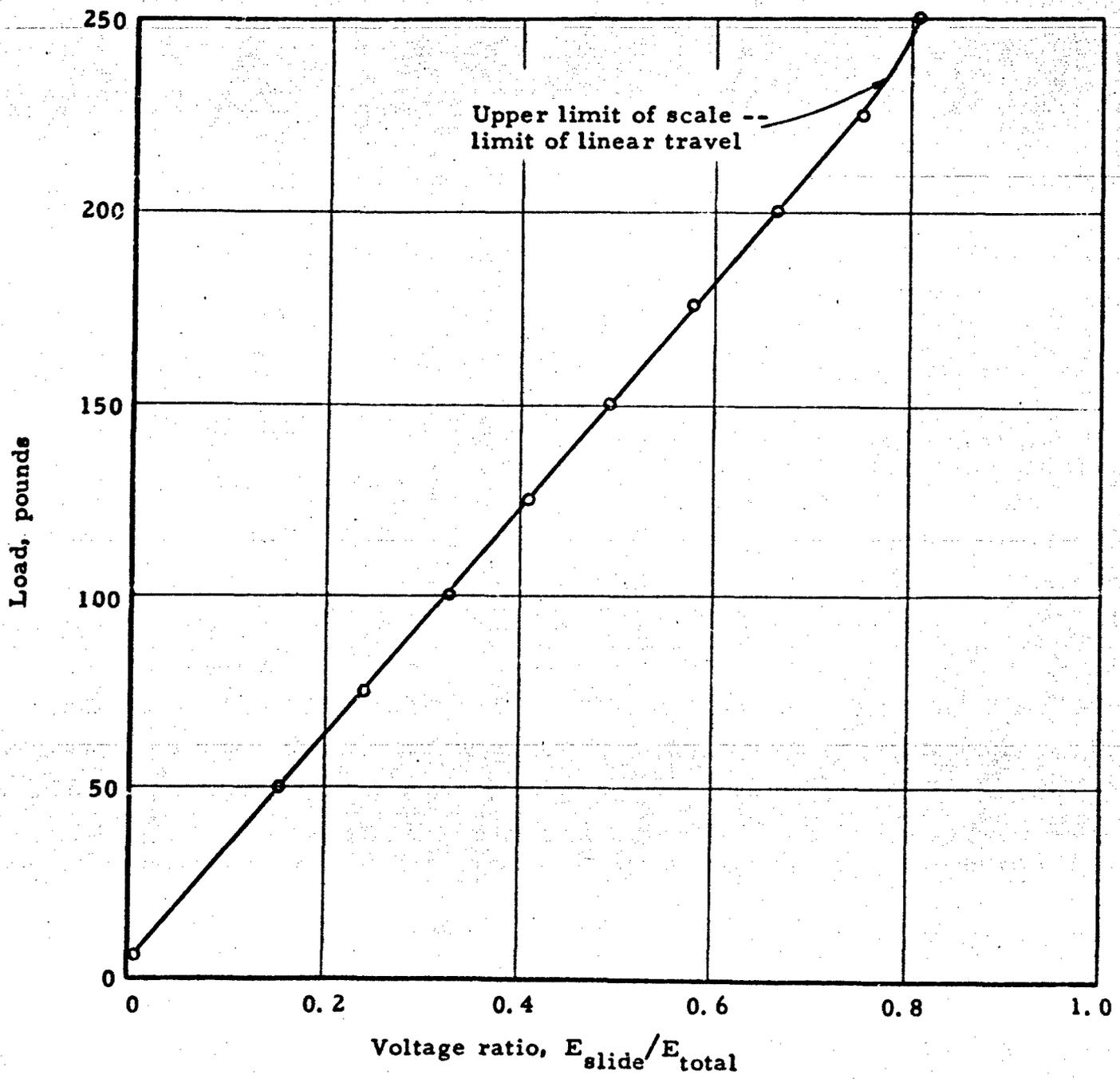


Figure A-9. Typical Scale Calibration Curve

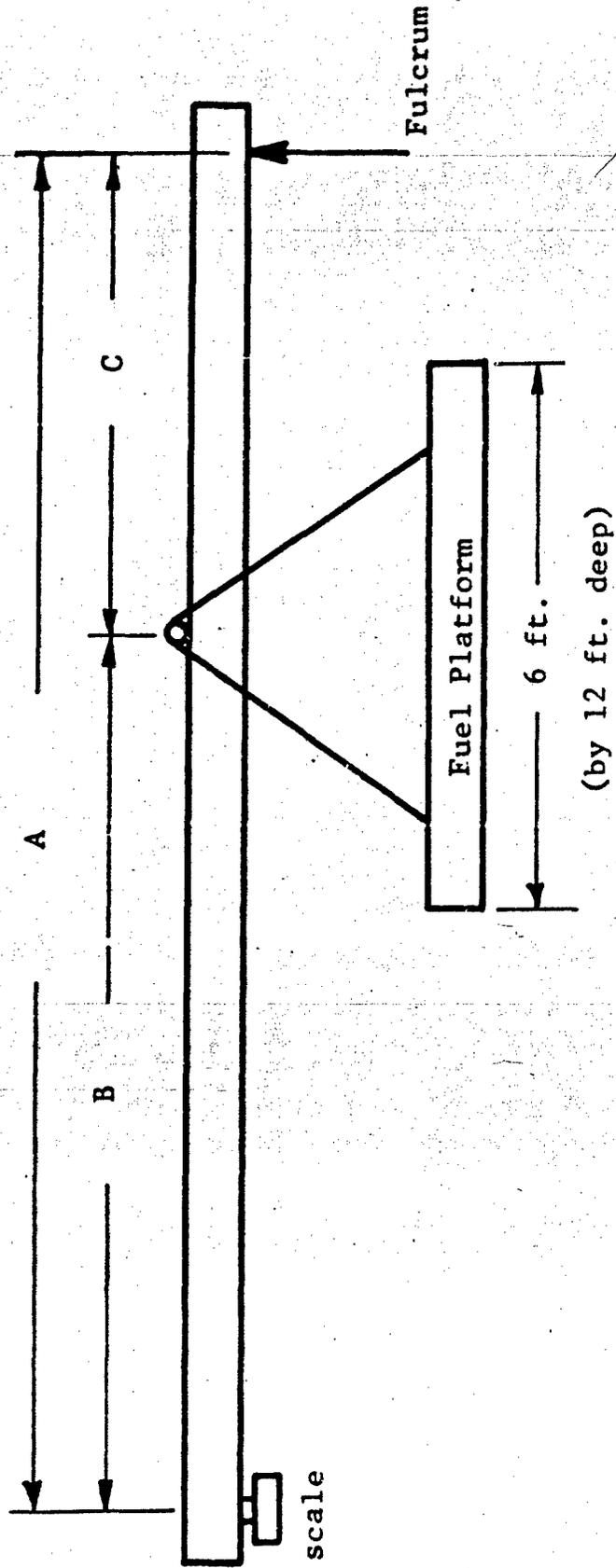
in excess of that of a single scale. In addition, it was desirable to protect the scales from the full intensity of the fire. Both difficulties were overcome by placing the fuel (crib) on a platform suspended from two parallel protected wood beams. Each beam was supported on a fulcrum at one end and on a scale at the other end as shown in Figure A-10. The fulcrum points were within the room but the scales were on the outside window sill and were shielded from the fire. (See Figure A-11).

4. Gas Analysis

Gas samples were drawn from selected locations within each structure through copper tubing or black iron pipe. Once clear of the structure, each sample line was connected to a cooler and moisture trap. From the traps, the samples were drawn through polyethylene tubing to a bank of solenoid operated valves controlled by a timed step-switch where the lines were sequentially passed through the analyzers. Lines not being analyzed were bypassed to the pump to maintain a continuous flow of fresh samples from the building.

The oxygen analyzer was a continuous unit using the paramagnetic properties of oxygen. In operation, the unit supplies the gas sample by diffusion to each of two resistors forming legs of a Wheatstone bridge. By placing a magnetic field through one of the resistor chambers, cool oxygen-rich gas is drawn to this resistor. Once heated, the oxygen loses its magnetic properties and is forced out of the way by cooler,

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Actual Weight Loss = $\frac{A}{C}$ (sum of scale weight losses)

Building	A	B	C
1	181"	117"	64"
2	180"	120"	60"

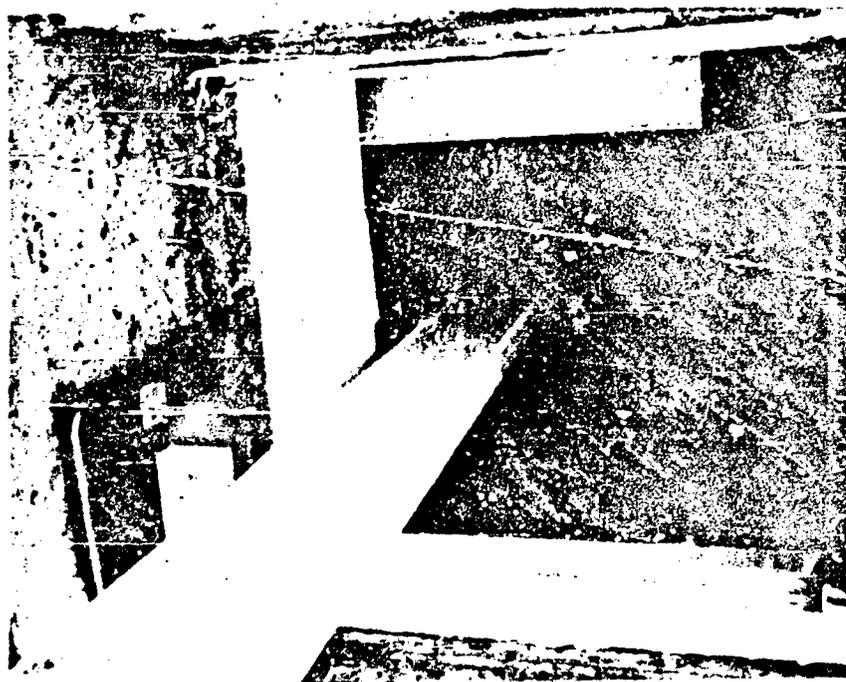
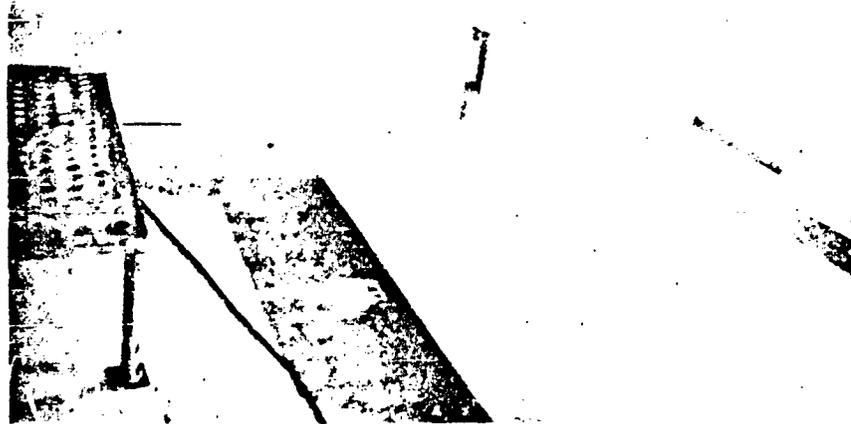


Figure A-11. Arrangement for Measuring Burning Rate in Buildings 1 and 2

more magnetic oxygen-rich gas diffusing into the chamber. The additional cooling of the resistor in the magnetic field results in a resistance change which is noted in the bridge circuit and may be recorded.

Carbon monoxide concentrations were measured by two means. The first of these (used on Buildings 1 and 2) was with a combustibles analyzer. The principle of operation is the catalytic combustion of the gas sample on a heated filament. As the filament also has a high temperature coefficient of resistance, the combustion causes a measurable change in resistance which is related to the amount of combustible present. A Wheatstone bridge circuit is again used to produce a signal suitable for recording.

The above-described system for CO measurement has not proven entirely satisfactory due to catalyst poisoning. This occurred during cool-down or extinguishment of any given fire experiment and was noted as a loss of calibration (a reference gas was connected to one of the sampling positions). For this reason, an infra-red system using the absorption by CO of selected wavelengths was used to obtain a portion of the CO data from Building No. 2 and all of the CO data from Building No. 3.

5. Pressures

Pressure differences were monitored with diaphragm gauges having full-scale deflection for 1.0 inch water. In

Buildings 1 and 2, copper tubes, originating on either side of each barrier to be monitored, were run horizontally as a pair to the building exterior and then down to a location common to all lines, where the gauges and a clock were recorded photographically (see Figure A-1). For Building 3, linear variable differential transformers (LVDT's) were attached to each gauge. The diaphragm movement of the gauge thus produced a corresponding movement in the transformer core. The core movement produces an unbalance in A.C. signals from the transformer. Demodulation of these unbalanced signals produces a D. C. voltage proportional to the core displacement.

6. Stop Motion Photography

Sixteen mm film records of all experiments were taken at 50 frames per minute. Kodachrome II film (ASA 25 daylight) was found sufficiently fast to permit exposures at 1/50 second with a variable shutter camera. The inclusion of a clock in all pictures permitted rapid correlation of film records with the other measured parameters.

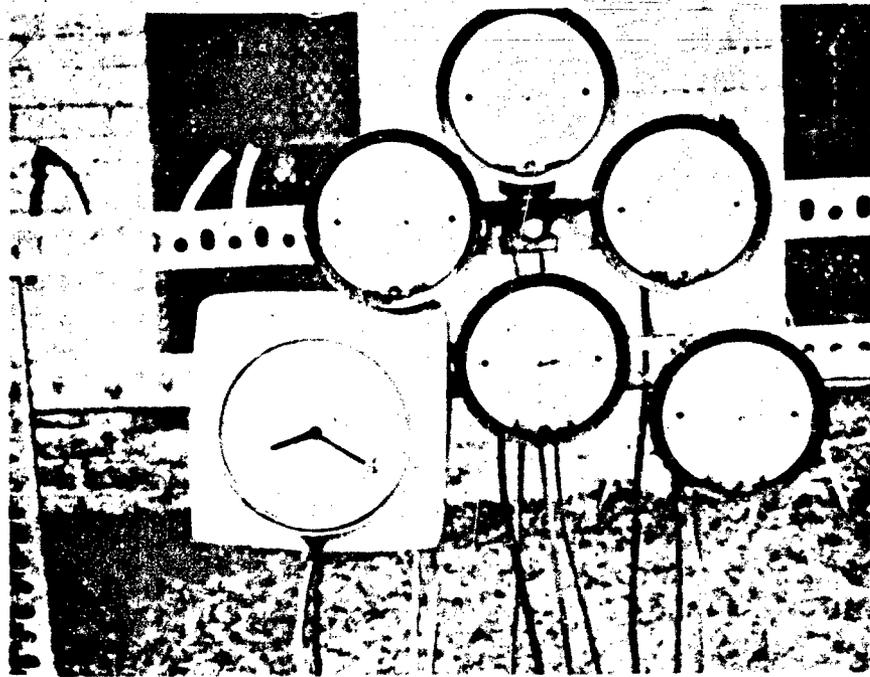


Figure A-12. Arrangement of Pressure Gauges
Used in Buildings 1 and 2

APPENDIX B
EXTINGUISHMENT STUDIES

Previous studies⁽¹¹⁾ have shown that the suppression of fires in an urban area exposed to a nuclear burst will depend considerably on the effectiveness of semi-professional fire-fighting units referred to as "brigades". A brigade has been defined as a fire-fighting unit consisting of four men capable of extinguishing room fires after flashover using one-inch booster lines and spray nozzles. The reason for limiting the brigades to small diameter hose lines is the requirement for the most efficient use of water following a nuclear attack. In this regard it has been proven by experimental means⁽¹¹⁾ that the suppression of one or two fully-involved residential room fires can be accomplished with the least amount of water when booster lines are used. Such information is not available for fires involving large areas, both from the viewpoint of the ability to suppress the fire by small diameter hose lines and the amounts of water required. Since the brigades may constitute the major fire-fighting force during a nuclear emergency, their effectiveness in suppression of large fires is of vital interest.

An opportunity of obtaining data on the effectiveness of brigades in suppression of large fires arose during the Waukesha experiments. Although the suppression aspects were not originally specified as a part of the program plan, it

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was felt that such information should be obtained and suppression experiments were included as a part of the burns in Building 3 which was the largest of the three structures.

The space selected for the experiments was a room 60 x 90 ft. and containing 24 windows. The combustible content (Figure B-1) consisted of scrap lumber giving a fire load of $9\text{-}1/4 \text{ lb/ft}^2$. The instrumentation consisted of ten thermocouples and photographic equipment; locations of the thermocouples are shown in Figure B-2. Photographic equipment was placed in the front and to the side of the structure to record both the fire-fighting operations and patterns of the discharged water streams. The fire suppression was performed by the Waukesha Fire Department.

Four suppression experiments were conducted. For the first experiment, the fire was started using JP-4 fuel. Complete extinguishment was not executed; water was applied only to the point when the fire was judged to be under control. The fire was then allowed to rekindle for the next experiment. In each case, fire suppression commenced when the space became fully involved in the fire as determined by visual observation.

The total water discharge rate (gal/min) was about the same in all experiments and each experiment used a different number and size of hose line. Thus it was possible to use the same base for evaluating the effectiveness of the various water streams. The discharge rate used was determined prior to



Figure B-1. Fire Load in Ignition Room of Building No. 3

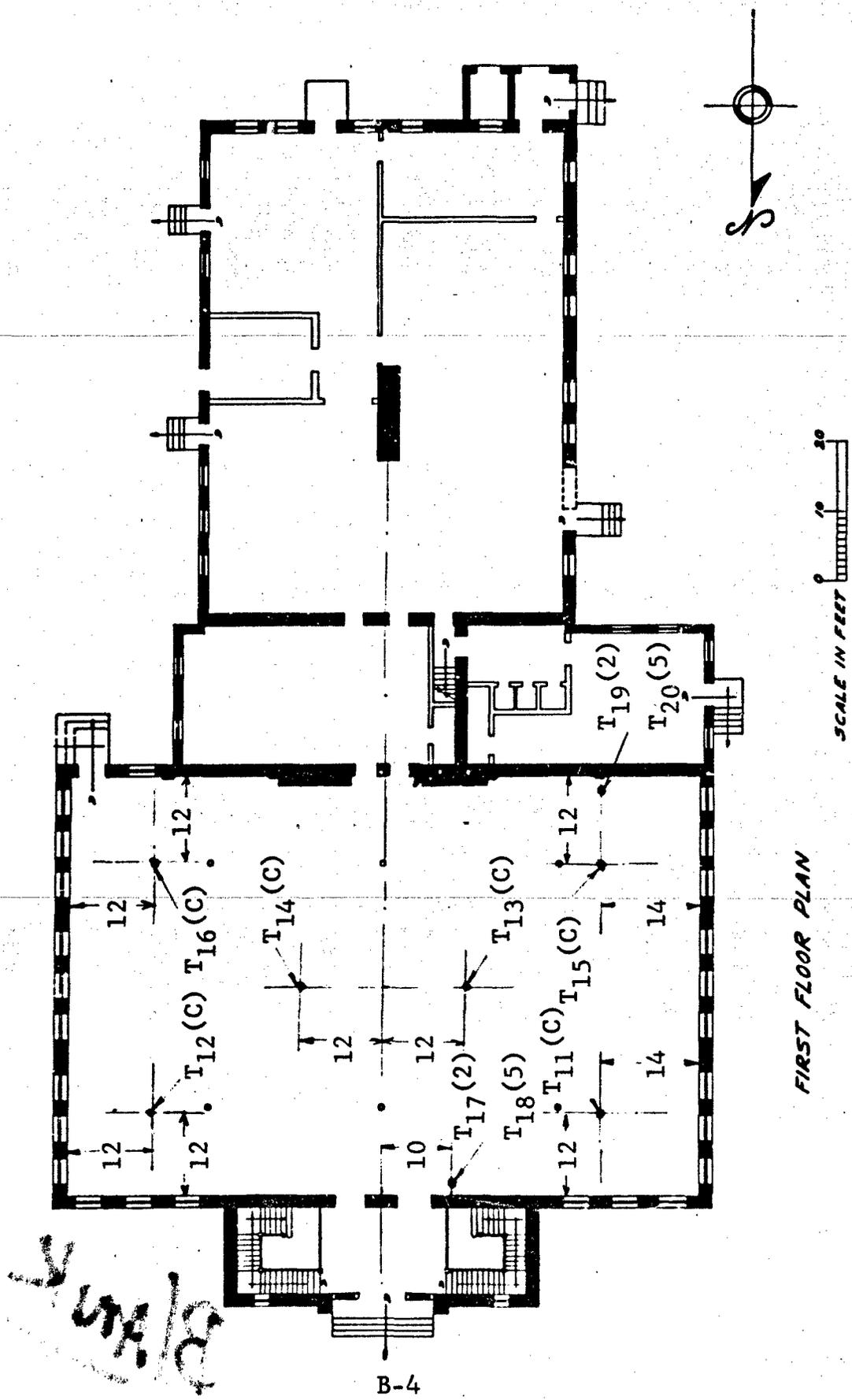


Figure B-2. Thermocouple Locations in Building No. 3

the experiments by extrapolating the relationship obtained previously between the application rate and the amount of water required to suppress one and two room fires⁽¹¹⁾

The total amount of water expended in each experiment is shown in Table B-1. As can be seen, the use of eight 1-1/2 inch lines required much less water than the 2-1/2 inch lines. This may be explained, possibly, by the differences in the uniformity of water application. The eight lines distributed the water more evenly over the fire whereas the effectiveness of the three lines was reduced by the localized concentrations of water. This difference in the effectiveness is also illustrated by the thermocouple readings shown in Fig. B-3. The first extinguishment produced quite uniform cooling as seen from thermocouples 12, 14, 16 and 11, 13, and 15. The second extinguishment was slightly less effective in cooling the fire due to lack in reach by the fog streams into the room center; (thermocouples 13 and 14 did not show the same temperature drop as 11, 12, 15, and 16). The third extinguishment gave very spotty cooling as shown by the readings of Thermocouples 11, 13, and 15. In the fourth experiment, all of the water from the turret did not reach the fire and the experiment was judged to be inconclusive.

Experiments have shown that fires involving large spaces, such as found in commercial occupancies, can be

TABLE B-1

SUMMARY OF EXTINGUISHMENT EXPERIMENTS

Exp. No.	<u>Hose Lines</u>		Type of Spray	Total Application Rate (gpm)	Total Gallons Used
	Number	Diameter (in.)			
1	8	1-1/2	straight	760	266
2	8	1-1/2	30° fog	760	266
3	3	2-1/2	straight through 1-1/8 in. tip	750	625
4	1	turret pipe		800	inconclusive

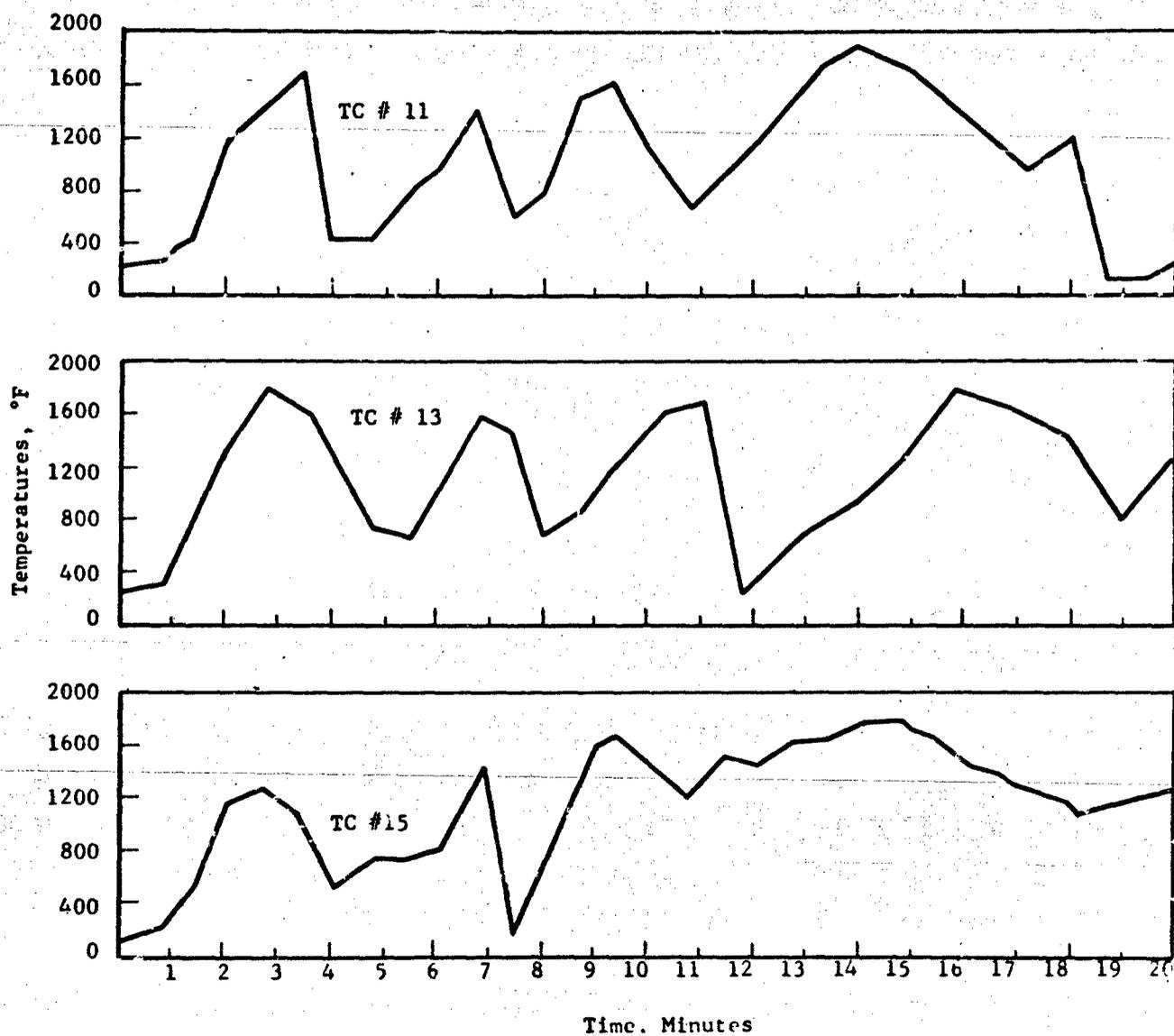


Figure B-3A. Temperatures in Building No. 3 Burn

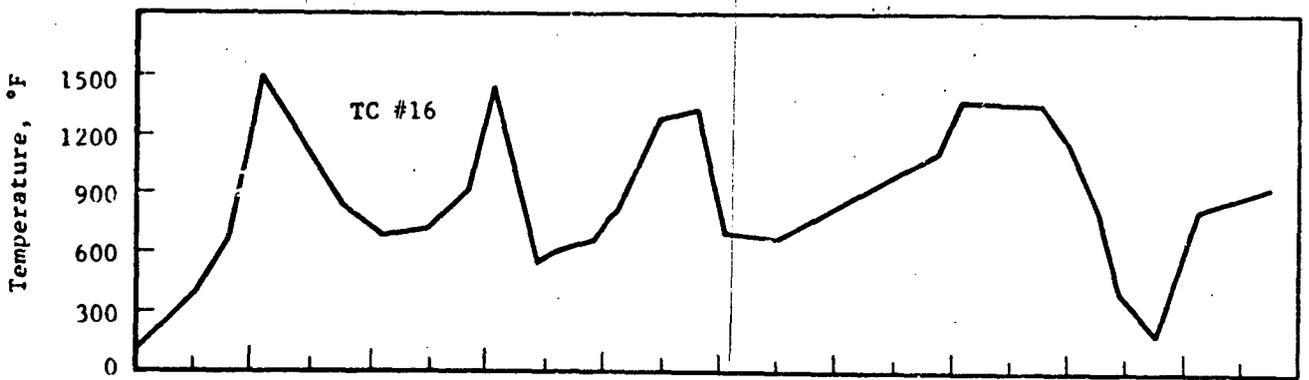
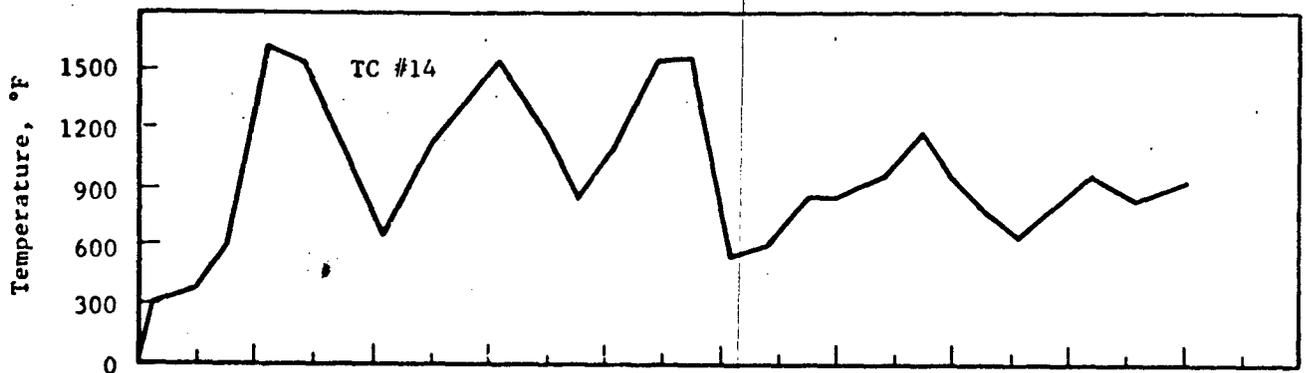
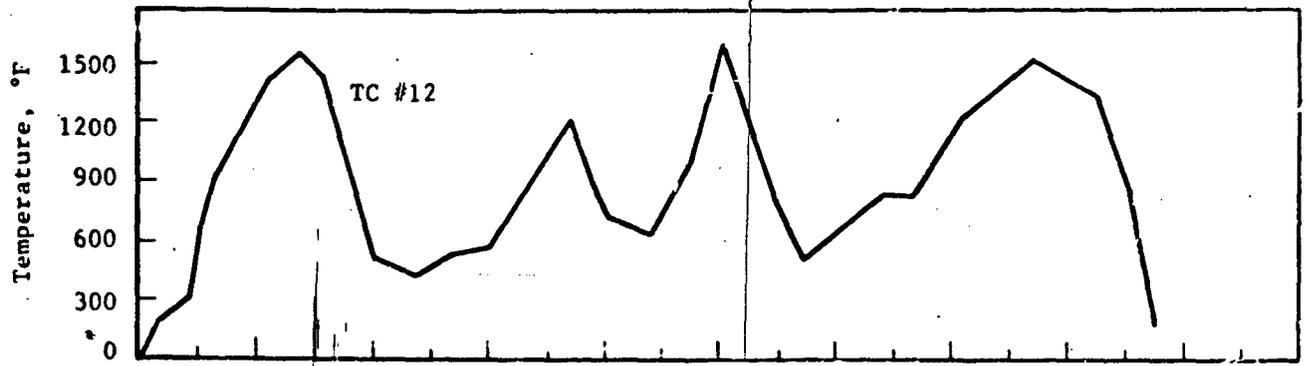


Figure B-3B. Temperatures in Building No. 3 Burn

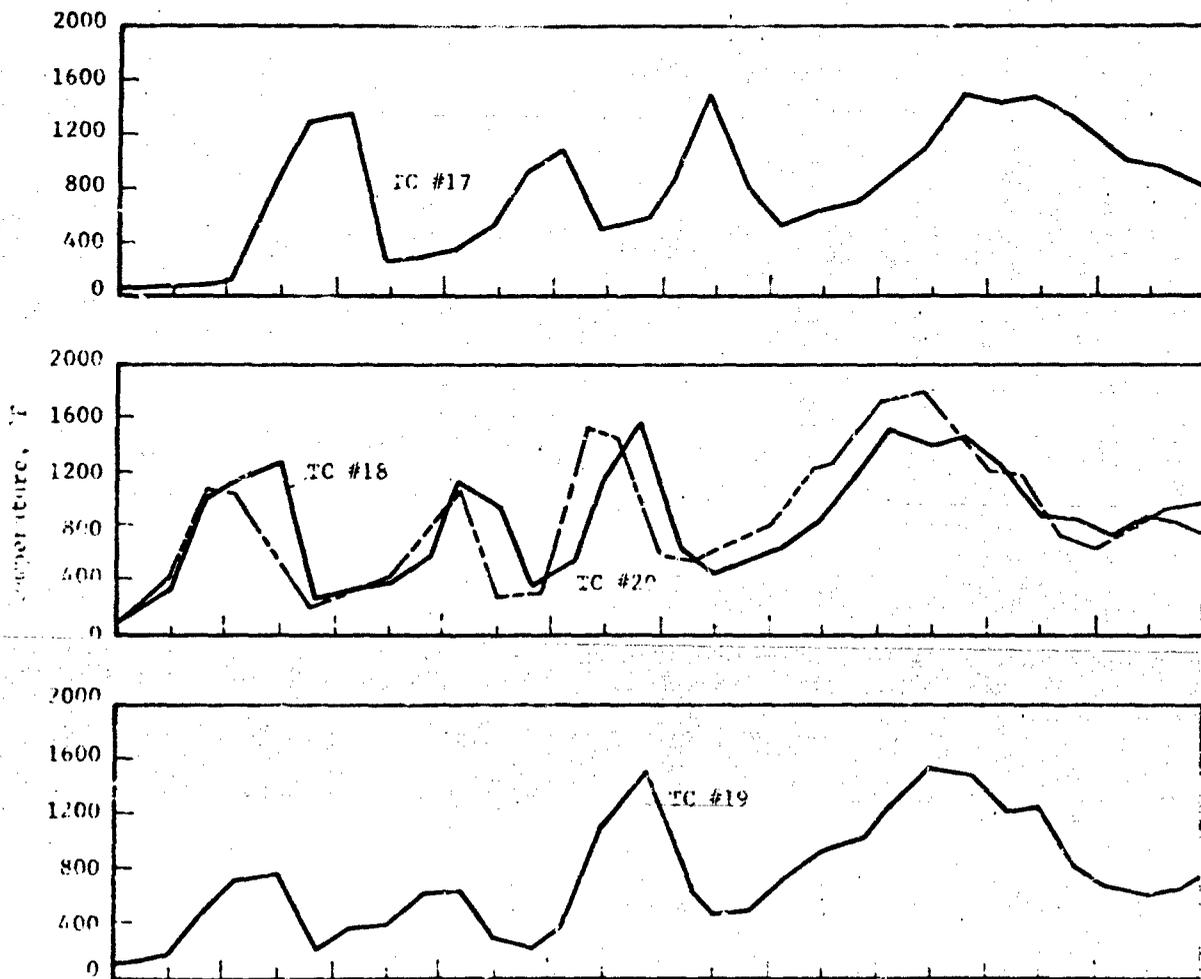


Figure B-3C. Temperatures in Building No. 3 Burn

effectively suppressed by the use of 1-1/2 inch hose lines. Thus, present findings confirm the conclusions of the past studies⁽¹¹⁾ which recommend the use of brigades as the primary force for suppression of fires caused by a nuclear burst.

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B-10

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13. ABSTRACT Experiments were performed in full scale buildings to obtain information regarding the habitability of fallout shelters in existing buildings under fire exposure. One two-story and two three-story buildings of masonry and wood joist construction were used. The fire load of the room of fire origin consisted of a large crib (2 x 4 inch lumber) with the remainder of the structures loaded with furniture typical of residential construction. Results indicate that oxygen depletion in an active fire zone will be reproduced throughout interconnecting spaces. Carbon monoxide concentrations of 75 percent of those in the active fire zone were found at places removed from the fire but on the same or higher levels. For these buildings, wind-induced pressure differences were greater than fire-induced pressure differences and thus would have had greater effect on the infiltration of fire gases through shelter barriers. The long lasting effects debris fires in contact with the shelter were found to produce dangerous heating of the shelter.			